US Mines Bureau

[redacted]

DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
JOSEPH A. HOLMES, DIRECTOR

THE SIGNIFICANCE OF DRAFTS IN STEAM-BOILER PRACTICE

BY

WALTER T. RAY

AND

HENRY KREISINGER

TN
23
U4
no. 21

ENGINEERING

[Reprint of United States Geological Survey Bulletin 367]

ENGIN STORAGE

WASHINGTON
GOVERNMENT PRINTING OFFICE
1911

Bulletin 21

DEPARTMENT OF THE INTERIOR
BUREAU OF MINES
JOSEPH A. HOLMES, DIRECTOR

THE
SIGNIFICANCE OF DRAFTS IN STEAM-BOILER PRACTICE

BY

WALTER T. RAY

AND

HENRY KREISINGER

190742
3/9/24.

[Reprint of United States Geological Survey Bulletin 367]

WASHINGTON
GOVERNMENT PRINTING OFFICE
1911

Digitized by the Internet Archive
in 2011 with funding from
University of Toronto

http://www.archive.org/details/bulletinu21unit

CONTENTS.

	Page.
Preface	5
Introduction	7
Drafts and their significance	9
Experiments by the Geological Survey at Norfolk, Va., on the pressure drops of gases passing through furnaces	13
Laboratory experiments relative to the flow of gases through boilers	22
Effect of pressure drop through the fuel bed on rate of combustion and on evaporation	44
Steaming tests by the Geological Survey at St. Louis, Mo	47
Locomotive tests by the Geological Survey and the Seaboard Air Line Railway at Portsmouth, Va	53
Summary	59
Glossary	62

ILLUSTRATIONS.

Page.

FIG. 1. Cause of reduced pressure in the base of a high chimney 10

2. Relation of pressure drops taken over fuel bed, in combustion chamber and in uptake, boiler equipment No. 6 13

3. Relation of pressure drops through fuel bed and through boiler, boiler equipment No. 6 14

4. Pressure drops through boiler equipment No. 5 16

5. Pressure drops through boiler equipment No. 7 17

6. Diagram showing pressure drops through a hypothetical boiler 20

7. Apparatus for studying flow of air through beds of shot 23

8. Relations between pressure drops through lower beds of No. 8 shot and flow of air 24

9. Relations between pressure drops through lower beds of No. 4 shot and flow of air 30

10. Relations between square roots of pressure drops through lower beds of No. 8 shot and rates of flow of air 31

11. Relations between thickness of lower beds of No. 8 shot and flow of air 33

12. Relations between thickness of lower beds of No. 4 shot and flow of air 34

13. Relations between total pressure drops and drops through lower beds of No. 8 shot 37

14. Relations between total pressure drops and drops through lower beds of No. 4 shot 38

15. Relations between thickness of lower bed of No. 8 shot and pressure drops through it 39

16. Relations between thickness of lower bed of No. 4 shot and pressure drops through it 40

17. Relations between pressure drops through lower beds of No. 8 shot and flow of air 42

18. Relations between pressure drops through lower beds of No. 4 shot and flow of air 43

19. Relations between total pressure drops and flow of air for several constant pressure drops through lower beds of No. 8 shot 44

20. Relations between total pressure drops and flow of air for several constant pressure drops through lower beds of No. 4 shot 45

21. Relations between pressure drops through two boilers and stated items 48

22. Relations between pressure drops through two fuel beds and stated items with varying pressure drops through boilers 49

23. Relations between pressure drops through two fuel beds and stated items with constant pressure drops through boilers 50

24. Relations between pressure drops through two boilers and stated items 51

25. Relation between total pressure drop and rate of combustion and percentage of CO_2 in flue gases 52

26. Relation between total pressure drop and horsepower developed 57

PREFACE.

The study of the principles underlying the movement of gases through furnaces and boilers suggested itself to the authors during the early work of the Government fuel-testing plant at St. Louis, Mo. At that time the members of the steam-engineering section were perplexed with the results of a series of tests made on the same coal. It was found that during this series of tests the capacity developed by the boiler was apparently independent of the draft in the furnace, that is, some tests run with higher drafts in the furnace showed lower capacity than some other tests run with lower drafts in the furnace. Later on, after a large number of steaming tests had been made with the two Heine boilers, the results were studied with the object of finding the effects of drafts on the capacity developed by the boiler and on other items of the results of the tests. Charts 21 to 24, inclusive, are the results of this study. Although these charts show that some relation exists between the drafts and the results of the tests, this relation is shown in an indefinite way, owing to the presence of many other influencing factors.

Early in 1908, after the suspension of regular fuel tests at the fuel-testing plant at Norfolk, Va., the writers took up the study of "draft" again. They decided to make a series of experiments with a laboratory apparatus in order that they might easily eliminate all variables except the ones they wished to study, such elimination being impossible in experiments with a large boiler. These laboratory experiments gave very consistent results, which furnished material for a rational study of the laws governing the movement of gases through steam-generating apparatus.

Although the laws that were deduced from the experiments strictly apply only to the isothermal flow of gases, nevertheless the writers thought that the deductions would be applicable to a large extent to flows of gases in a steam boiler. The writers were not disappointed in their expectations; during the last two years they have had many opportunities to see how closely the deductions which they had drawn from the laboratory experiments applied to large boilers and to gases of varying temperatures.

It is the hope of the writers that this bulletin will be a help in solving many a vexatious problem pertaining to "drafts" in boiler plants. The theme of this bulletin is perhaps not presented in the best and most easily comprehended way, but it must be remembered that the subject of drafts had been given little attention, and no definite and precise terms were developed which could convey ideas accurately; therefore, long phrases often had to be used where one word of definite meaning would have made the statements more concise and clear. For this reason, the study of the bulletin will require closer attention than the study of an ordinary report of a boiler test wherein terms are employed that have been standardized by long usage and have definite meanings.

Those who do not wish to study the whole bulletin may find practical deductions and summaries on pages 11, 12, 32, 41, 42 to 47 and 59.

THE SIGNIFICANCE OF DRAFTS IN STEAM-BOILER PRACTICE.

By **Walter T. Ray** and **Henry Kreisinger.**

INTRODUCTION.

This preliminary bulletin was written as the first of a series of several on the significance of drafts in steam-boiler practice, the succeeding bulletins to be along the same lines but of a more advanced character. The conclusions arrived at are tentative, and are the result of a study of one of the many problems growing out of a general plan of the United States Government to increase the efficiency with which the coals of the country are being used. Greater efficiency requires better boiler and furnace design.

The experimental study of drafts on which the conclusions presented in this bulletin are based formed part of the fuel-testing investigations that were carried on by the technologic branch of the United States Geological Survey and have been transferred to the Bureau of Mines.

The experiments made seem to indicate that it is possible to double or treble the capacity of a plant without making any radical changes in the furnaces and boilers. These increases require about double and treble the quantities of air to be put through the fuel beds and boilers. It also seems probable that rebaffling the boilers will often permit the capacity to be doubled or trebled, while still getting more steam than formerly per pound of coal for uses outside the boiler room.

These experiments were undertaken with the object of clarifying ideas concerning the passage of air through fuel beds and boilers. Measured weights of air were passed through two beds of lead shot, in series, one of which remained always the same and represented a boiler; the other being varied as to size of shot and depth of bed, and representing a fuel bed. Careful observations were made of the weight of air passing through the beds per minute. All data were plotted in many charts, so as to permit the study of them from several points of view. A number of laws were deduced bearing on the relative amounts of power required to force air through fuel beds of various thicknesses, composed of various sizes of coal, and through boilers of various lengths and areas of gas passages.

An important part of the discussion relates to an increase in the capacity of boilers by increasing the amount of power applied to pressure and exhausting fans and thus forcing several times as much air through the fuel beds and boilers.

It may be possible, as a result of these investigations, to raise the rate of working the boiler heating surface to three or even four times its present value. Such an increase would undoubtedly mean new designs of grates, stokers, furnaces, and boilers, especially fitted for high rates of working. Fan equipments designed to supply three or four times as much air under several times the pressure would be provided with more efficient engines, thus giving an additional factor favoring high-capacity working.

It must be borne in mind, as stated above, that the results are tentative. It will cost money to force gases at high speeds through fuel beds and boilers, and there will soon be pressing need of such quantitative data as will enable the largest possible part of the energy imparted by the fans to be advantageously utilized.

We desire to thank our superiors, especially Messrs. L. P. Breckenridge and D. T. Randall, for their helpful criticism and suggestions.

DRAFTS AND THEIR SIGNIFICANCE.

In the steam-boiler furnace the hot fuel is made to burn by passing a current of air through it. This current of air supplies the necessary oxygen and carries away the gaseous products of combustion. In order that the boiler may absorb the heat generated by combustion and contained in the gases leaving the fuel bed, the gases are caused to flow along the heating plates of the boiler and to impart heat to them by coming into contact with their surfaces. The stronger the current of air through the fuel bed the higher the rate of combustion; and, likewise, the stronger the current of gases over the heating surfaces the faster the boiler seems to absorb heat. It is thus evident that the motion of the air and of the gases of combustion is very essential to the operation of a furnace and boiler. The motion of gases is produced by an excess of pressure at any point over that at any other point toward which the gases are flowing; the greater the pressure difference the higher the velocity of flow. The word "draft" is loosely applied sometimes to the motion of gases and sometimes to the difference of pressure producing the motion. In order to avoid ambiguity and the giving of false impressions as to the cause of motion of gases, the word will ordinarily not be used in this bulletin. A moment's consideration of the likelihood that a gas is a discontinuous body will make it clear that there can really be no such motive cause as "draft."

There are three ways of producing such differences of pressure as will cause gases to flow through the fuel bed and boiler—(1) by chimneys, (2) by exhausting fans between boilers and chimneys, and (3) by pressure fans supplying air under the grate.

1. The use of high chimneys is most common. They reduce the pressures inside their bases so that the greater pressure of the atmosphere outside pushes air through the fuel bed and gases of combustion through the boilers into their bases. The reduction of pressures is due to the fact that gases expand when heated, in consequence of which the chimneys contain smaller weights of gases than they would if chimneys and gases were cold. We then have the weight of a column of hot gases in the chimney pressing against the gases in the uptake, and the weight of a column of air of the same dimensions and at atmospheric temperature pressing against the air in the ash pit.

Referring to figure 1, let w be the weight of the column of hot gases in the chimney, and W the weight of a column of outside air of the same dimensions; then the difference (d) between the pressures in the ash pit and the uptake will be the difference between the weights of these two columns when both have unit area of cross section, or $d = \mathrm{W} - w$.

The same equation will be obtained if we include in the calculations the weights of the columns of air above the chimney and above the aforementioned imaginary column of cold air outside the chimney. Let the weights of these columns be A (see fig. 1); then the total weight pressing against the ash-pit door is $\mathrm{A} + \mathrm{W}$ and the total weight pressing against the gases in the uptake is $\mathrm{A} + w$. Therefore the difference, $d = \mathrm{A} + \mathrm{W} - (\mathrm{A} + w) = \mathrm{W} - w$, as before.

As a result of this difference of pressure the outside air pushes the furnace gases into the chimney and through it into the high open atmosphere. The air which has been pushed through the fuel bed into the furnace is partly modified by the combustion, which produces more furnace gases, which are in turn pushed out through the chimney into the open air.

It is evident that the hotter the gases in the chimney the more they are expanded and the lighter they are, and the greater is the difference of gas pressure between the front of the furnace and the base of the chimney; also that the higher the chimney the greater is the difference of pressure.

The heat energy left in the column of gases escaping from a boiler is not entirely wasted, as part of it is used in keeping up the continuous current of gases. By raising the temperature of the gases the same difference of pressures between the uptake and the front of the furnace can be had by a low chimney as by a high one, although such a method would not be economical. Anything which reduces the temperature of the gases while in the stack reduces the magnitude of the pressure difference between the chimney base and the furnace doors; on this account less coal can be burned and less steam made. It follows that a steel stack without any brick lining on the inside is, on account of the high thermal conductivity of the steel, not as efficient as a brick one, provided the latter is absolutely tight, as is seldom or never the case.

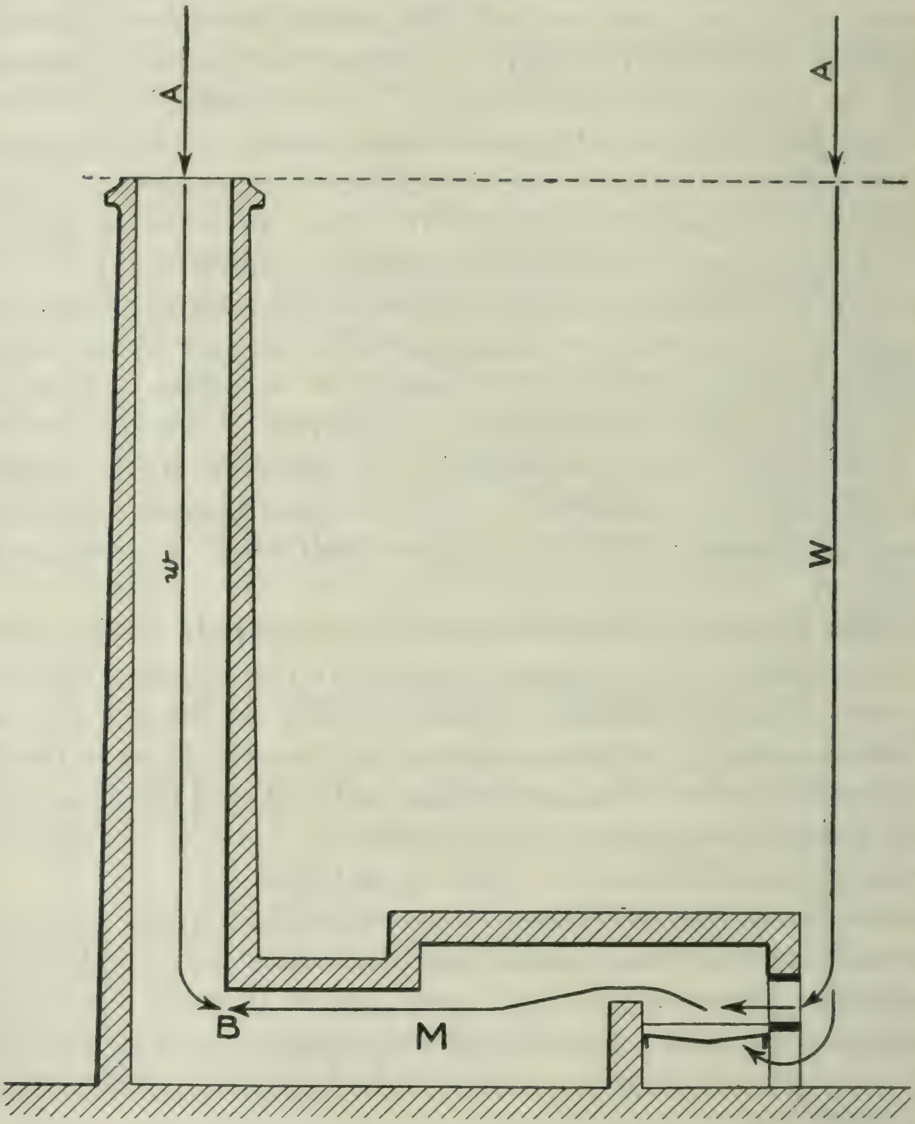

FIG. 1.—Cause of reduced pressure in the base of a high chimney.

2. Another common method of reducing the gas pressure in the uptake of a boiler setting is by an exhaust fan. Usually it is said that the exhaust fan sucks or pulls the gases through the boiler; in reality no such action can occur. The blades of the fan push the gases out of the casing, thereby reducing the pressure in it below that in the

furnace; the excess of pressure in the furnace then pushes other gas through the boiler into the space of reduced pressure inside the fan casing, and so the current continues.

3. Another way of producing an excess of gas pressure under the grate over that in the uptake is by connecting a pressure blower or fan to the space under the grate, so as to increase the pressure therein above that of the atmosphere. In some cases the whole fireroom is put under pressure. This method is ordinarily termed the "forced-draft" method, in contradistinction to the "induced-draft" method. There is, however, no essential difference between the two. Occasionally they are used together.

In practice the pressures of the gases in the various parts of the boiler setting are measured by instruments called draft gages, the pressures being usually expressed in inches of water. The zero points are or should be atmospheric pressure. With an exhaust fan between the uptake and the stack the pressure anywhere in the boiler setting is below that of the atmosphere and is lowest at the edges of the blades next the shaft. With a pressure fan applied to the ash pit or fireroom the pressure under the grate is above that of the atmosphere. At the top of the stack the pressure is the same as the atmospheric pressure at that particular elevation; this pressure is always lower than that at the base of the stack.

The drop of gas pressure from one part of the boiler setting to another varies as some power of the resistance to the flow of gases. Thus a great drop from ash pit to furnace indicates a high resistance in the fuel bed, and a great drop from the furnace to the uptake indicates a high resistance to the flow of gases through the boiler proper. This law, which in some respects is similar to Ohm's law, as applied to problems involving the electrical resistance of conductors, may be stated as follows:

(*a*) If the resistance to the flow of gases remains constant the pressure drop through any portion of the path of the gases will have a constant ratio to the total drop from the ash pit to the uptake. Thus, for example, if the pressure drop through the fuel bed is 0.50 inch of water when the total drop is 1.0 inch, it will be 1.0 inch if the total drop be increased to 2.0 inches, and 2.0 inches if the total drop be increased to 4.0 inches of water.

(*b*) If the total pressure drop from the ash pit to uptake remains constant, the pressure drop through any portion of the gas path will vary in the same direction as does the resistance to the flow of gases, although the magnitudes of the variations may not be in simple proportion. Suppose the total pressure drop is 1.0 inch of water, and the drop through the fuel bed is 0.5 inch; now, if the total drop be kept the same but the resistance through the fuel bed be increased by doubling its thickness, the pressure drop through the fuel bed will increase to about 0.65 inch of water; or if, for the same total drop, the resistance of the fuel bed be increased by quadrupling the thickness, the drop through the bed will increase to about 0.80 inch of water.

(*c*) When the resistance through any portion of the gas path remains constant the weight of gas passing through this portion varies with some power of the pressure drop through this portion. Thus, since the resistance of that portion of the gas path from over the fuel bed to the uptake is ordinarily very nearly constant, the weight of gases passing through the furnace and boiler varies as some power of the pressure drop between these points. Approximately only, the weight of gases passing through the boiler is directly proportional to the square root of the pressure drop through the boiler or through any other portion of the gas path having constant resistance.

Of the above three statements, only the one under *a* is exactly parallel to Ohm's law of the drop of electrical potential through conductors of constant resistances.

The relation between drops of pressure and the resistance to the flow of gases expressed by the statement under *b* is similar to Ohm's law only in the direction of the variation, not in its magnitude. In Ohm's law the relation between the drop of potential through any portion of the conductor and the resistance is very simple; that is, the drop of potential is directly proportional to the resistance. In the case of the flow of gases, however, the analogous relation between pressure drop and resistance seems to be either an exponential or a logarithmic function. In fact, no definite relation can be stated at present because the unit of resistance is not clearly defined.

The statement under *c*, expressing the relation between the pressure drop and the weight of gas passing through a furnace and boiler, comes closer to Ohm's law than that made under *b*. If the exponent of the power were 1.0 the relation would reduce to Ohm's law; that is, when drop of pressure is considered as drop of potential and the weight of gases flowing per second as the current.

The preceding statements are deductions from the study of experimental results obtained on large boilers and on small laboratory apparatus; the details of the results are given in succeeding portions of this bulletin.

EXPERIMENTS BY THE GEOLOGICAL SURVEY AT NORFOLK, VA., ON THE PRESSURE DROPS OF GASES PASSING THROUGH FURNACES.

Figures 2 to 5 are submitted as practical proof of the statement under *a*, which asserts that if the resistance to the flow of gases remains constant the pressure drop through any portion of the path of the gases will always bear a constant ratio to the total drop.

Pressures were taken in each case almost simultaneously at two or more points in the boiler setting. All the observations of any one figure were taken in a total time of only a few minutes, so that the resistance of the fuel bed remained substantially constant. The resistance to the flow of gases through any boiler is probably very closely constant at all times; also, owing to the shortness of the time occupied in taking any one set of readings, the fuel bed remained very closely of the same temperature and mechanical porosity. It is especially worthy of note that the circumstances of the fuel bed

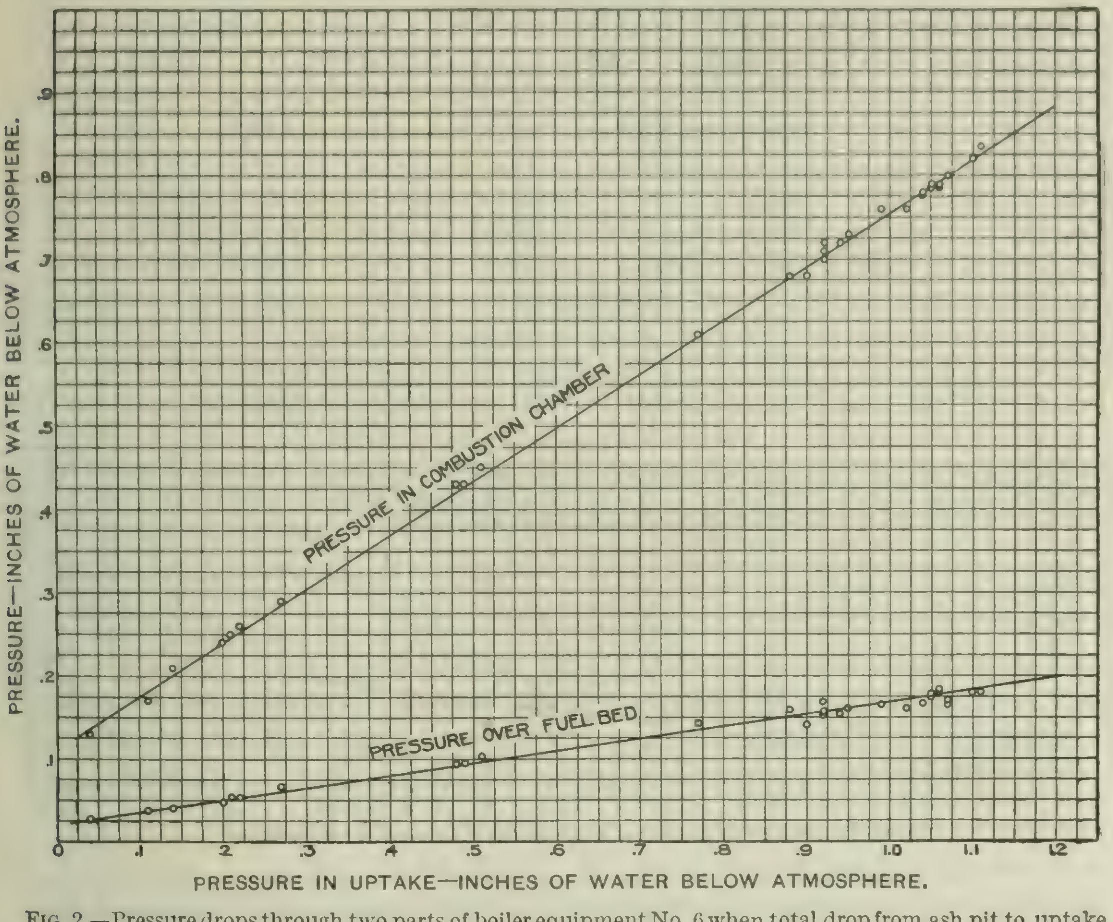

FIG. 2.—Pressure drops through two parts of boiler equipment No. 6 when total drop from ash pit to uptake is varied and the resistances to the flow of gas are kept constant. The upper curve gives the relation between the pressure drop from ash pit to combustion chamber and the total pressure drop from ash pit to uptake. The lower curve gives the relation between the pressure drop through grate and fuel bed and the total drop from ash pit to uptake.

being hot and the gases of varying temperature at different times and at different points did not curve any of the lines; the fact that they were not curved is explicable if we consider that the intrinsic resistance of the fuel bed is probably a function only of the size and shape of the air passages through it. It must be constantly borne in mind, however, that the amount of air passing through an opening under the same pressure difference is greatly affected by the temperature of the air.

Tables 1, 2, 3, and 4 contain the original data and computations thereon from which were platted figures 2, 3, 4, and 5, respectively.

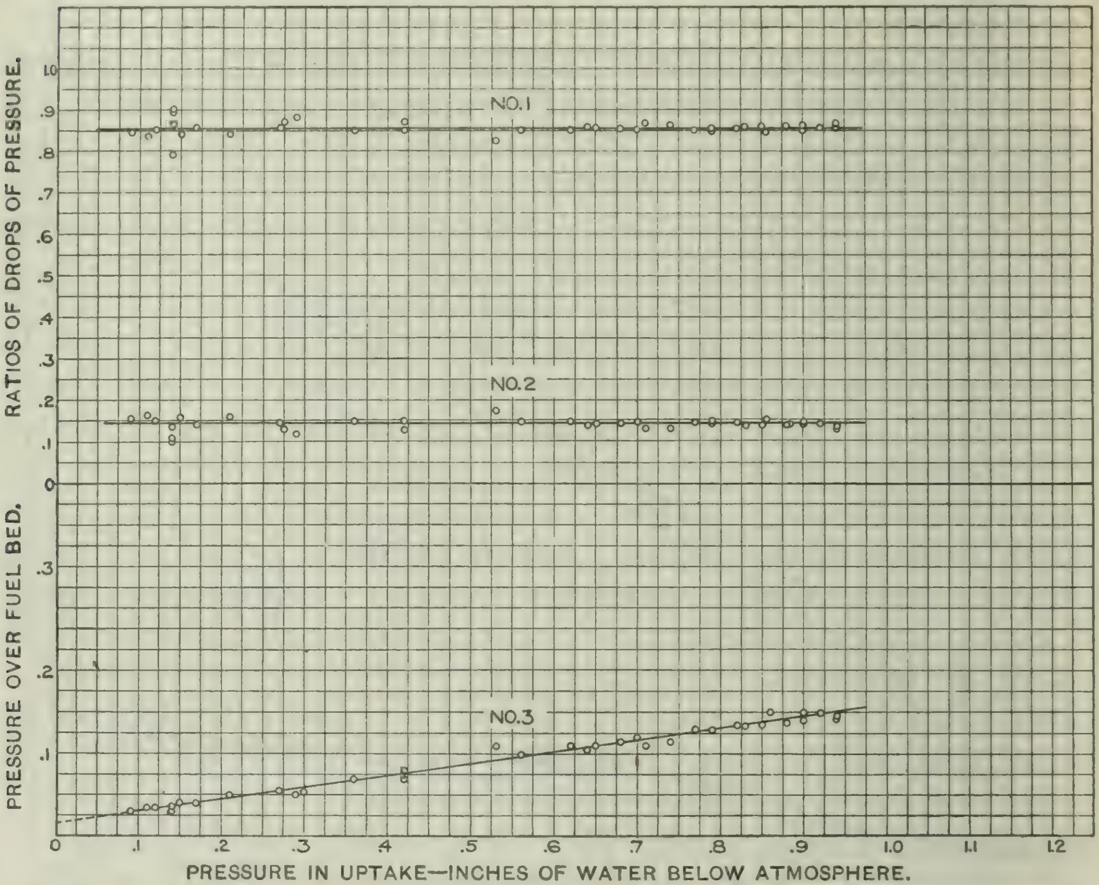

FIG. 3.—Pressure drops through two parts of boiler equipment No. 6 when the total drop is varied and the resistances to the flow of gas are kept constant. Curve No. 1 gives the ratio of the pressure drop through the boiler (from over fuel bed to uptake) to the total pressure drop from ash pit to uptake. Curve No. 2 gives the ratio of the pressure drop through the grate and fuel bed to the total drop from ash pit to uptake. Curve No. 3 shows the relation between the pressure drop through grate and fuel bed and the total pressure drop from ash pit to uptake.

It will be noticed that the lines usually do not go through zero, which is because the "draft" gages were not absolutely correct; but the errors are very small.

The data given in Table 1 and plotted in figure 2 were obtained on boiler outfit No. 6, which consisted of a hand-fired Heine boiler operated at the time with an exhaust fan. Among the tubes of this boiler had been inserted one horizontal baffle in such a position as to cause the gases to travel forward among the lower two-thirds of the tubes and backward among the upper one-third to the point of exit. The heating surface of the drum was omitted.

TABLE 1.—*Data obtained September 30, 1907, on boiler No. 6 by opening and closing more or less the damper just beyond the uptake in front of the exhaust fan.*

[Pressure in ash pit atmospheric. All pressures are expressed in equivalents of inches of water.]

1	2	3	1	2	3
Pressure below atmosphere over fuel bed.	Pressure below atmosphere in rear of combustion chamber.	Pressure below atmosphere in uptake.	Pressure below atmosphere over fuel bed.	Pressure below atmosphere in rear of combustion chamber.	Pressure below atmosphere in uptake.
0.165	0.8	1.07	0.054	0.25	0.21
.17	.8	1.07	.048	.24	.2
.16	.76	1.02	.037	.17	.11
.142	.68	.90	.178	.79	1.06
.154	.7	.92	.178	.79	1.05
.094	.43	.48	.17	.78	1.04
.055	.26	.22	.172	.79	1.05
.042	.21	.14	.168	.78	1.04
.18	.83	1.11	.17	.72	.92
.18	.82	1.10	.029	.13	.04
.16	.73	.95	.067	.29	.27
.154	.72	.94	.102	.45	.51
.155	.71	.92	.142	.61	.77
.165	.76	.99	.159	.68	.88
.094	.43	.49	.182	.79	1.06

NOTE.—The pressures (drafts) given in this table are not quite correct, because the gages were not accurate. Therefore the ratio of column 2 to column 3, for instance, is not constant, as it should be, especially where the pressures are low. For a corrected set of readings on the same boiler outfit see Table 2.

The pressures platted in figure 2 as abscissæ were taken about 2 feet in front of the damper located near the entrance of the gases into the fan. The ash-pit doors were open to the atmosphere. The scales at the left-hand side of the figure and along the bottom are correctly named as pressures and not as "drafts;" the coordinates are expressed in inches of water below atmospheric pressure.

The variations in the gas pressure in the uptake were obtained by partially opening and closing the damper located between the uptake and the exhaust fan. Readings of pressures at different points were taken in rapid succession immediately after each change of the damper position. The figure shows that the points fall along straight lines as closely as the instruments could be read. The two curves indicate that the pressure drops at the three places bear a constant relation to one another. This constant relation follows because the ratios of the resistances are constant.

The data given in Table 2 (p. 18) and platted in figure 3 were taken on the same outfit as the data for figure 2; the gas pressures were varied in the same manner. It will be noticed that the slopes of the lower line of figure 2 and of curve 3 of figure 3 are very nearly the same, whence the deduction may be made that the fuel beds in the two cases were of very nearly the same resistance to the passage of air. Curve 1 of figure 3 gives the ratio of the pressure drop through the boiler (that is, from "over fuel bed" to "uptake") to the total pressure drop from the ash pit to the uptake; curve 2 gives the ratio of the drop of pressure through the grate and fuel bed to the total pressure drop from the ash pit to the uptake. These curves were obtained by platting from Table 2 the values of columns 7 and 8, respectively, as ordinates and of column 1 as abscissæ. Columns 7 and 8 were calculated from the corrected pressures over fuel bed given in column 5, which latter are 0.016 lower than the observed values given in column 2. The amount of the correction was determined by prolonging curve 3 of figure 3 to the line of zero pressure in the uptake; at this line the corresponding pressure drop from ash pit to over fuel bed should be also zero; therefore the indicated (incorrect) pressure above the fuel bed at the line of zero pressure in the uptake was applied as a correction to all the observed readings of pressure over the fuel bed. It is noticeable that the ratios given

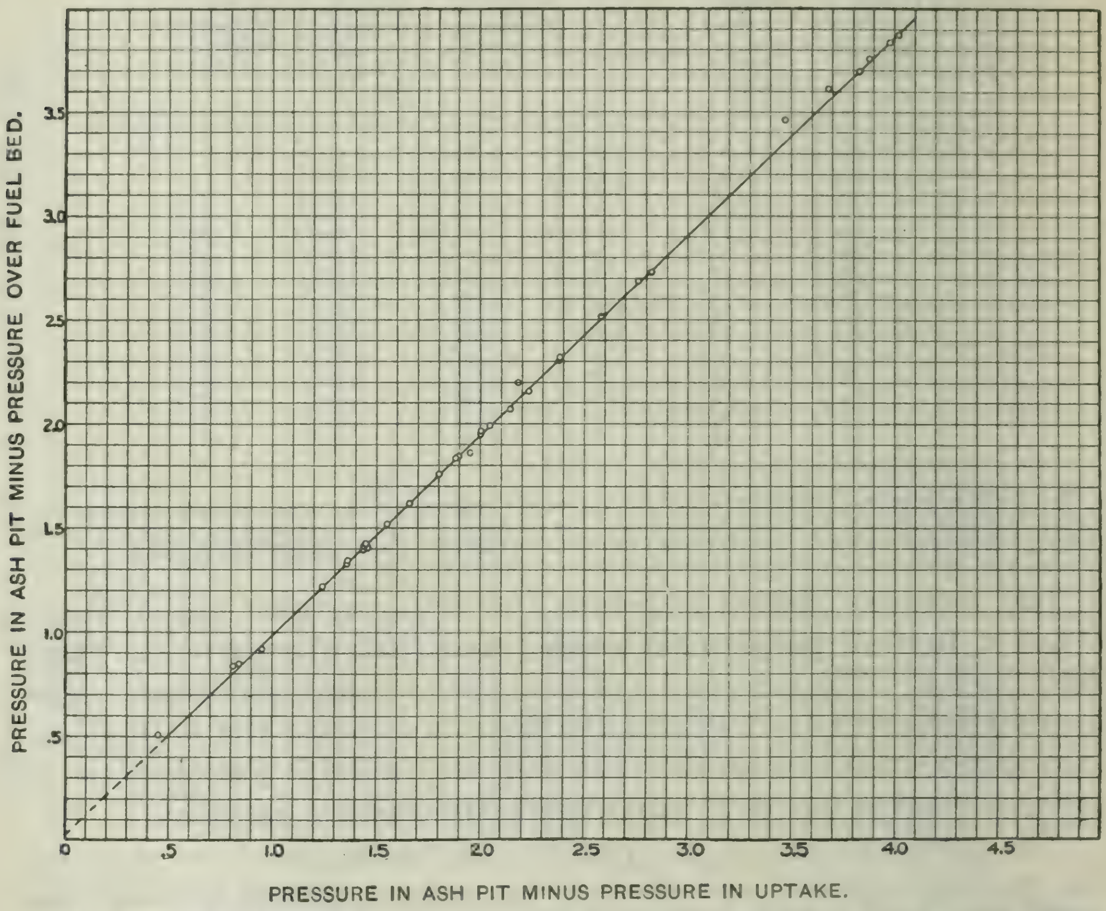

FIG. 4.—Pressure drops through boiler equipment No. 5. Drop from ash pit to uptake varied. Heine boiler with standard baffling and underfeed stoker.

in columns 7 and 8 are much more uniform than those given in column 4; the latter being figured from the uncorrected pressures of column 2. However, both the corrected and the uncorrected figures show that the ratio of the drop through the boiler to the total drop through fuel bed, combustion chamber, and boiler is constant. The same constancy pertains to the ratio of the drop of pressure through the fuel bed to the total drop. Both curve 1 and curve 2 signify that the ratio of pressure drops is constant when the respective resistances remain constant.

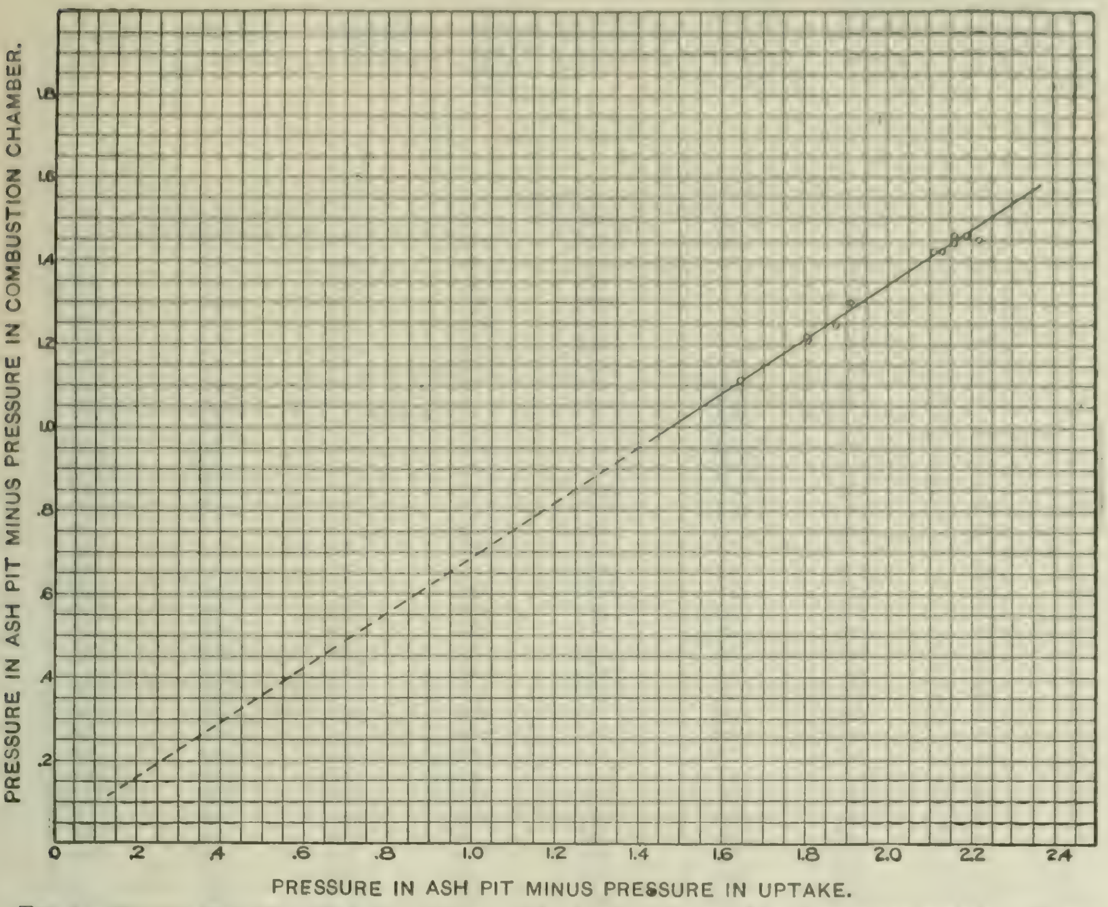

FIG. 5.—Pressure drops through boiler equipment No. 7. Drop from ash pit to uptake varied. Babcock & Wilcox boiler, semimarine type, equipped with front overfeed stoker.

Table 2.—*Experiment made September 28, 1907, on boiler No. 6 to determine the ratio of the pressure drop through the boiler (that is, from top of fuel bed to uptake) to the total pressure drop from the ash pit to the uptake.*

[All pressures are stated in equivalents of inches of water.]

Pressure in uptake below atmosphere.	Pressure over fuel bed below atmosphere.	Drop of pressure from over fuel bed to uptake.	Ratio of column 3 to column 1.	Corrected pressure over fuel bed below atmosphere.	Column 1 minus column 5.	Ratio of column 6 to column 1.	Ratio of column 5 to column 1.
1	2	3	4	5	6	7	8
0.70	0.12	0.58	0.828	0.104	0.596	0.852	0.148
.56	.10	.46	.822	.084	.476	.851	.149
.36	.07	.29	.806	.054	.306	.850	.150
.15	.04	.11	.734	.024	.126	.840	.160
.14	.03	.11	.786	.014	.126	.900	.100
.71	.11	.60	.845	.094	.616	.868	.132
.77	.13	.64	.832	.114	.656	.852	.148
.79	.13	.66	.836	.114	.676	.856	.144
.85	.135	.715	.842	.119	.731	.860	.140
.94	.145	.795	.846	.129	.811	.862	.138
.21	.05	.16	.762	.034	.176	.839	.161
.14	.035	.105	.750	.019	.121	.865	.135
.68	.115	.565	.832	.099	.581	.855	.145
.79	.13	.66	.836	.114	.676	.856	.144
.88	.14	.74	.841	.124	.756	.859	.141
.90	.15	.75	.834	.134	.766	.851	.149
.92	.15	.77	.837	.134	.786	.854	.146
.82	.135	.685	.836	.119	.701	.855	.145
.62	.11	.51	.823	.094	.526	.849	.151
.27	.055	.215	.796	.039	.231	.855	.145
.17	.040	.13	.765	.024	.146	.859	.141
.88	.14	.74	.841	.124	.756	.859	.141
.29	.05	.24	.828	.034	.256	.883	.117
.30	.055	.245	.817	.039	.261	.870	.130
.12	.034	.086	.716	.018	.102	.850	.150
.74	.115	.625	.845	.099	.641	.866	.134
.94	.114	.796	.847	.128	.812	.864	.136
.42	.07	.35	.834	.054	.366	.872	.128
.42	.08	.34	.810	.064	.356	.848	.152
.11	.034	.076	.691	.018	.092	.836	.164
.64	.105	.535	.836	.089	.551	.861	.139
.90	.140	.76	.844	.124	.776	.862	.138
.83	.133	.697	.840.	.117	.713	.859	.141
.65	.110	.540	.831	.094	.556	.856	.144
.14	.030	.11	.786	.014	.126	.900	.100
.090	.030	.06	.667	.014	.076	.845	.155
.53	.110	.42	.792	.094	.436	.823	.177
.86	.150	.71	.825	.134	.726	.844	.156

The data given in Table 3 and platted in figure 4 were obtained on a Heine boiler equipped with a Jones underfeed stoker; the boiler was baffled in the standard Heine fashion (unlike the Heine boiler from which were obtained the data for figs. 2 and 3). The table is divided into two parts. Part 1 was obtained by keeping the air pressure in the ash pit as nearly constant as feasible and varying the pressure (below atmospheric) in the uptake; part 2 was obtained by keeping the pressure in the uptake as nearly constant as feasible and varying the pressure in the ash pit. All observations are arranged in chronological order.

On inspecting figure 4 it will be noticed immediately that the total pressure drop from ash pit to uptake was only a little greater than the pressure drop from the ash pit to the space just over the fuel bed. For instance, when the total pressure drop was 3.60 inches of water the drop through the tuyeres and fuel bed was nearly 3.50 inches, which left only a little more than 0.1 inch drop through the boiler. This latter figure was found to be substantially correct. The drop of pressure through the tuyeres alone is several times that through the boiler, and this pressure (and fan work) are uselessly absorbed unless it be the case that with some coals the high velocity of the air leaving the tuyeres serves to keep them clear of clinker and ash.

TABLE 3.—*Experiment made October 16, 1907, on boiler No. 5.*

[Part 1 was obtained by varying the pressure in the uptake while that in the ash pit was kept constant; part 2, by varying the pressure in the ash pit while that in the uptake was kept constant. All pressures stated in equivalents of inches of water.]

Part 1.					Part 2.				
Pressure above atmosphere in ash pit (blast).	Pressure below atmosphere over fuel bed (draft).	Pressure below atmosphere in uptake (draft).	Pressure drop through grate and fuel bed equals column 1 plus column 2.	Pressure drop through grate, fuel bed, and boiler equals column 1 plus column 3.	Pressure above atmosphere in ash pit (blast).	Pressure below atmosphere over fuel bed (draft).	Pressure below atmosphere in uptake (draft).	Pressure drop through grate and fuel bed equals column 1 plus column 2.	Pressure drop through grate, fuel bed, and boiler equals column 1 plus column 3.
1	2	3	4	5	1	2	3	4	5
1.5	0.45	0.50	1.95	2.00	....	....	....	....	....
1.7	.29	.34	1.99	2.04	....	....	....	....	....
1.9	−.04	.05	1.86	1.95	....	....	....	....	....
2.2	.00	−.02	2.20	2.18	....	....	....	....	....
2.2	.32	.38	2.52	2.58	....	....	....	....	....
2.3	.39	.46	2.69	2.76	....	....	....	....	....
2.3	.43	.52	2.73	2.82	....	....	....	....	....
....	....	....	....	....	0.9	0.49	0.54	1.39	1.44
....	....	....	....	....	.9	.51	.55	1.41	1 45
....	....	....	....	....	.7	.52	.54	1.22	1.24
....	....	....	....	....	.4	.53	.55	.93	.95
.5	.35	.34	.85	.84	....	....	....	....	....
.5	.01	−.05	.51	.45	....	....	....	....	....
.45	.39	.36	.84	.81	....	....	....	....	....
.42	.53	.54	.95	.96	....	....	....	....	....
....	....	....	....	....	.9	.51	.54	1.41	1.44
....	....	....	....	....	.9	.50	.53	1.40	1.43
....	....	....	....	....	1.35	.50	.54	1.85	1.89
....	....	....	....	....	1.35	.49	.53	1.84	1.88
....	....	....	....	....	1.85	.46	.53	2.31	2.38
....	....	....	....	....	1.85	.47	.53	2.32	2.38
....	....	....	....	....	3.5	.38	.52	3.88	4.02
3.5	.11	.18	3.61	3.68	....	....	....	....	....
3.5	−.04	−.03	3.46	3.47	....	....	....	....	....
3.44	.32	.44	3.76	3.88	....	....	....	....	....
3.4	.30	.43	3.70	3.83	....	....	....	....	....
....	....	....	....	....	3.45	.39	.53	3.84	3.98
....	....	....	....	....	1.68	.48	.55	2.16	2.23
....	....	....	....	....	1.60	.47	.54	2.07	2.14
....	....	....	....	....	1.45	.51	55	1.96	2.00
....	....	....	....	....	1.25	.51	.55	1.76	1.80
....	....	....	....	....	1.1	.52	.56	1.62	1.66
....	....	....	....	....	2.0	.52	.55	2.52	2.55
....	....	....	....	....	.9	.52	.55	1.42	1.45
....	....	....	....	....	.8	.53	.56	1.33	1.36
....	....	....	....	....	.8	.54	.56	1.34	1.36

The data given in Table 4 and platted in figure 5 were taken on a Babcock & Wilcox boiler of the semimarine type, equipped with a Roney stoker, the whole apparatus being designated No. 7 in the

Geological Survey plant. At the time of the experiment the boiler was being operated with two fans, an exhaust fan located between the uptake and the stack and a pressure fan forcing air into the ash pit. The changes in uptake pressure were obtained by opening and closing more or less the damper between the uptake and the exhaust fan. For certain reasons only a small range could be covered that day, but the points lie as closely as could be expected along a straight line passing nearly through zero.

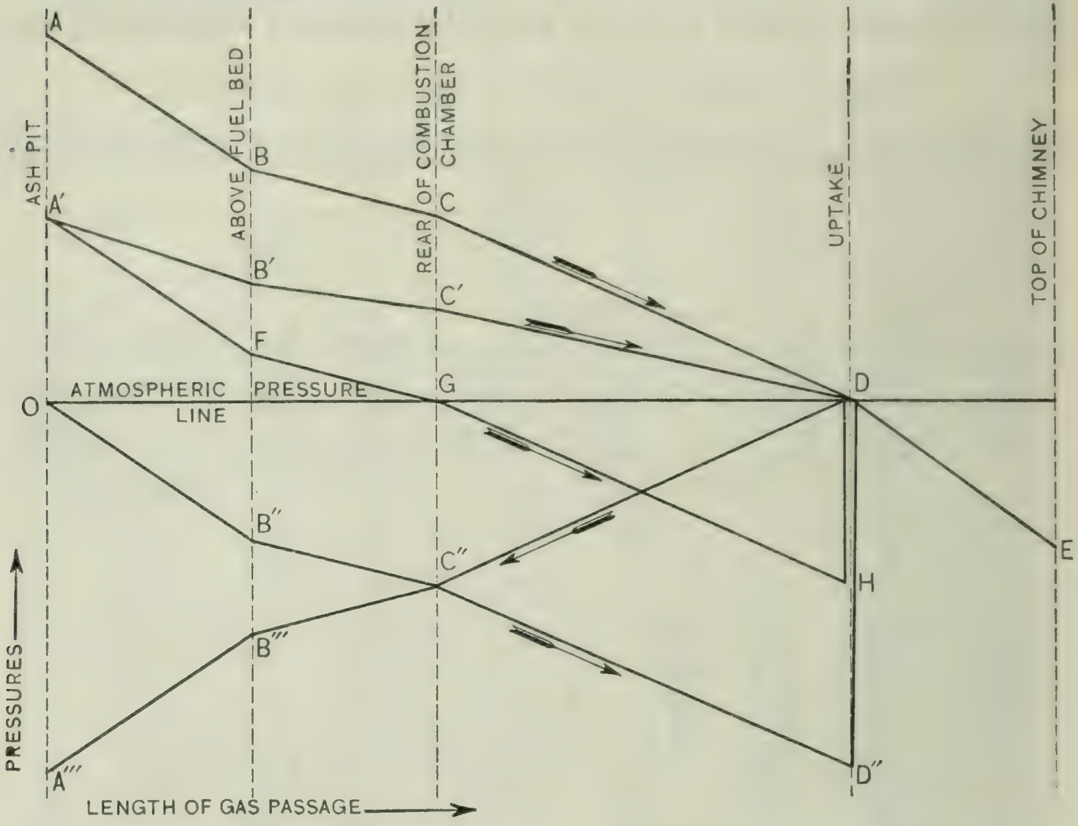

FIG. 6.—Pressure drops through a hypothetical boiler and equipment. The arrows represent directions of flow of gases. Line ABCDE represents pressure drops through the equipment when a fan is used to raise the pressure in the ash pit. Line A′B′C′DE represents the pressure drops through the equipment with the same fan running so as to give only half the pressure. Line OB″C″D″DE represents the pressure drop through the equipment when an exhaust fan is used to reduce the pressure in the uptake by an amount equal to D″D, the ash pit being open to the atmosphere. Line A′FGHDE represents the pressure drop through the equipment when both pressure and exhaust fans are used, but run with half the respective pressure effects of the first and third cases above. Line A‴B‴C″D represents what would be the pressure drop through the equipment if the exhaust fan of the third case above were connected to the ash pit and the uptake opened to the atmospheric pressure.

After studying the four charts just discussed it must be admitted that such a law as stated under *a* (p. 9) does exist; that is, with constant resistance the pressure drops through any two portions of the path of gas flow bear a constant ratio to one another.

We may, then, draw the diagram of figure 6. Let the lengths of the gas passages be represented along the line OE and the gas pressures at various places by perpendicular distances from this line. Pressures above atmospheric are shown above OE and those below atmospheric below it. The highest line, ABCDE, represents the drop in gas pressure through a fuel bed, combustion chamber, and boiler, when the pressure in the ash pit is above that of the atmosphere—that is, when, as is commonly said, "forced draft" is used. The points B, C, and D represent the gas pressures at the various parts of the equipment, as indicated in the figure. Now, suppose the blower be slowed down so as to give half the pressure in the ash pit, the condition of the fuel bed remaining the same. Then, according to figures 2 to 5, the pressures at all other points will be exactly halved. This case is represented by the line A′B′C′DE.

If the boiler and furnace are operated with an exhaust fan which lowers the pressure in the uptake by the same amount as the pressure fan in the first case raises the pressure in the ash pit, then in the diagram DD″ equals OA, and the pressure drop through the boiler setting is represented by the line OB″C″D″DE, of which the part OB″C″D″ is exactly parallel to line ABCD, when postulating that the total pressure drop and the respective resistances are the same in the third case as in the first.

TABLE 4.—*Data obtained October 2, 1907, on boiler No. 7, by opening and closing more or less the damper between the uptake and the exhaust fan.*

[The pressure fan which fed the air to the ash pit was not manipulated. All pressures are given in equivalents of inches of water.]

Pressure in ash pit above atmosphere (blast).	Pressure in rear of combustion chamber below atmosphere (draft).	Pressure in uptake below atmosphere (draft).	Absolute pressure in ash pit minus absolute pressure in combustion chamber (that is, pressure drop through grate, fuel bed, and combustion chamber) equals column 1 plus column 2.	Absolute pressure in ash pit minus absolute pressure in uptake (that is, total pressure drop through grate, fuel bed, combustion chamber, and boiler) equals column 1 plus column 3.
1	2	3	4	5
0.23	1.23	1.93	1.46	2.16
.24	1.22	1.95	1.46	2.19
.268	.94	1.54	1.208	1.808
.255	.96	1.55	1.215	1.805
.24	1.20	1.92	1.44	2.16
.278	1.02	1.63	1.298	1.908
.242	1.17	1.87	1.412	2.112
.21	1.20	1.92	1.41	2.13
.265	.87	1.38	1.135	1.645
.205	1.04	1.67	1.245	1.875
.20	1.24	2.02	1.44	2.22

Line $A'FGHDE$ represents the gas pressure drop when both the exhaust and pressure fans are used, but run at such slower speeds as to give about half the pressures of the first and third cases above.

The line $DC''B'''A'''$ is added to show what the gas pressures would be if the exhaust fan of the third case were connected to the ash pit and the uptake were opened to the atmosphere. Then (with the furnace fire doors closed) the three points A''', B''', and C'' would lie exactly as far below the atmospheric line as the corresponding points A, B, and C lie above it.

Figure 6 emphasizes the fact that there is no real difference between the so-called forced and induced "drafts," provided setting walls, doors, etc., are perfectly tight. Under such conditions "forced draft" does not crowd hot gases into far corners, nor does "induced draft" "suck" or "pull" gases out of them. The volumetric percentage of "dead" corners is exactly the same in either case, provided there are no leaks in or out. "With gases there is no pulling, only pushing," is a very truthful phrase. Gases always flow from a space of higher pressure to one of lower pressure, so that their absolute pressure entering a boiler must be greater than their absolute pressure leaving it. It does not matter whether the difference is obtained by raising the pressure in the ash pit above that of the atmosphere by the use of a pressure fan or by reducing the pressure in the uptake below that of the atmosphere by the use of an exhaust fan. So long as the differences of pressures at the two places are the same the velocities and the paths of the gases will be very nearly the same, inasmuch as under the low pressure differences ordinarily used the densities of the gases under the two circumstances are very nearly the same. To say that a chimney or exhaust fan sucks or pulls the gases through a boiler is as reasonable as to say that the condenser of a condensing engine sucks the piston during the latter part of the stroke.

LABORATORY EXPERIMENTS RELATIVE TO THE FLOW OF GASES THROUGH BOILERS.

In the pressure-drop experiments made on large boilers, the results of which are platted in figures 2 to 5, the resistances to the flow of gases were kept as nearly constant as possible, and only the total pressure drops were varied. It was desirable to make experiments in which the resistance could be varied so as to obtain data on which to base the study of the influence of the resistance on the pressure drop and on the weight of gases flowing through a boiler. To make such experiments on large boilers would not only be very expensive, but also inaccurate, because on such a large apparatus it would be difficult to control the conditions so as to have only one or two varying quantities while holding all the rest fixed. Those who have ever tried to get even relative figures on the resistances of hot coal beds, or who have attempted to measure the weight of gases flowing through a boiler, will realize how difficult, not to say hopeless, a task it would be to make such experiments on a large boiler. For these reasons it was decided to make these experiments on a simple laboratory apparatus specially arranged for the purpose.

The apparatus is shown diagrammatically in figure 7. It consists mainly of a glass tube which represents the boiler and a sheet-iron tank used for measuring the quantity of air. The glass tube is 1⅜ inches in internal diameter and 26 inches long. It is connected to the measuring tank with an iron pipe, and the pipe is hermetically sealed into the neck of the tank. The resistances of the fuel bed and of the boiler proper are represented by beds of shot placed in the tube, on coarse wire screens. Shot was selected for this purpose because of its regularity and uniformity of size and the comparative ease with which the aggregation of the spheroids with respect to one another can be reproduced. This latter is a very important matter, as will be shown later.

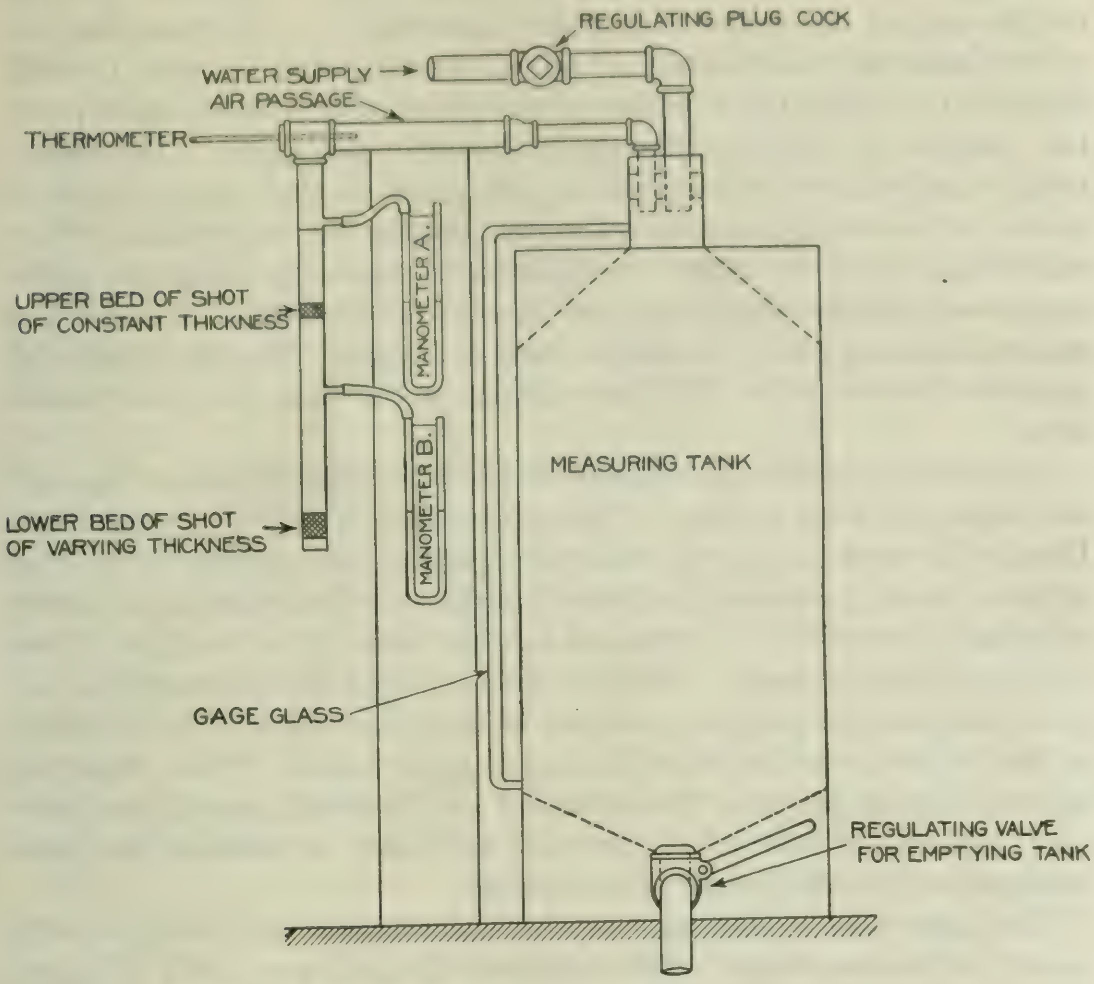
REGULATING PLUG COCK
WATER SUPPLY
AIR PASSAGE
THERMOMETER
UPPER BED OF SHOT OF CONSTANT THICKNESS
MANOMETER A.
MANOMETER B.
LOWER BED OF SHOT OF VARYING THICKNESS
MEASURING TANK
GAGE GLASS
REGULATING VALVE FOR EMPTYING TANK

FIG. 7.—Apparatus for studying flow of air through beds of shot.

Air was made to flow through the glass tube containing the two shot beds by filling and emptying the measuring tank with water, taken from the water-supply main, the latter supplying water under a pressure of about 35 pounds to the square inch. When filling the tank the flow of water was regulated with a plug cock in the water-supply pipe, and when emptying it with a quick-opening gate valve at the bottom of the tank; both of the valves are shown in the figure. By regulating these valves the flow of water into the tank and from it could be kept uniform. The pressures above each shot bed were measured by U-tube manometers which were connected to the middle and to the upper end of the glass tube. A thermometer for determining the temperature of the air was inserted into the flowing stream of air near the junction of the glass tube with the iron pipe; the position of the thermometer is shown in the figure. The measuring tank was provided with a gage glass so that the amount of water in the tank could be estimated during the experiment. The estimation could be made very accurately, especially when the water level reached the narrow neck at the top of the tank, in which the water displaced was 1 pound per inch of height. The tank held 636 pounds of water when full; the volume of the tank was 10.20 cubic feet.

Experiments were run with air flowing in either direction through the tube and beds of shot. The exact time of starting was noted. During the experiment one observer operated the proper valve so as to have the air pressures, indicated by the two manometers, as nearly constant as possible, the pressure seldom varying as much as 10 per cent from the average. Another observer read and recorded the air pressures and temperature as often as was convenient. At the close of the experiment the exact time was again noted. Thus, knowing the duration of the test, the volume of air displaced, and its temperature, the rate of flow of air for each difference of pressure and each thickness of shot bed could be computed.

The upper bed of shot was kept at the constant thickness of 0.875 inch in all experiments. The thickness of the lower bed was varied from 0.5 to 4.5 inches, and a set of 6 to 10 experiments was made with each thickness for each of the two sizes of shot, the experiments of each set being run at different air pressures. Thus the experiments in each set give the influence of air pressure on the flow of gas through a constant bed of shot, and the experiments in the different sets give the influence of the thickness and the relative resistances on the rate of flow. Two sizes of shot were tried in this manner, so as to get the effect of the diameter. Several sizes should have been used, but more time was not available.

In all 125 reliable tests were made. The first 74 were made with the lower bed of shot of commercial size No. 8, which were on the average about 0.0974 inch in diameter, and the last 51 tests were made on larger shot, known as No. 4, having an average diameter of 0.125 inch. The upper standard resistance bed was of the smaller shot and of the same thickness in all experiments.

Before the 125 reliable tests were run the whole series had been completed, but on comparing the worked-up data an inconsistency was discovered, and the whole series was rejected and all the tests were run over. While trying to account for the inconsistency it was recalled that in attempting to make the lower bed of shot an even number of inches thick in some cases part of the shot had been poured out of the tube when the layer happened to be a little too thick. When it was thought enough shot had been removed the tube was brought back into the vertical position and the bed leveled and measured. This process was repeated until the shot bed was of the desired thickness. It was found, when the shot bed had been thus adjusted by pouring shot out of the tube, that the voids among the shot were left much larger and that in consequence air passed through much more easily than when the shot was simply poured in and not deranged by pouring some of it out. Tests 52, 53, and 54 show the effect of the above-mentioned derangement; in these experiments exactly the same amount of shot was used as in tests 44 to 51, inclusive, but the aggregation was previously loosened by bringing the tube into a horizontal position as if to remove some of the shot, whereas in the regular experiments the shot was poured into the tube while holding the latter in a vertical position, the tube being kept vertical without jarring until the series of tests was completed. It will be seen on reference to the table that the derangement of the shot as described caused an increase of three-sixteenths of an inch in the thickness of the bed, making the depth 3.188 inches; it will also be seen that for the same pressure drop much more air flowed through the thicker (loosened) bed than through the 3-inch bed.

After having discovered the cause and the effect of the derangement all the experiments were run over, great care being taken to pour the shot into the tube from the same height and at the same rate. In case too much shot was poured in the first time it was all poured out, part of it separated, and the remainder poured back in the standard way. This process was repeated until the shot bed was of the desired thickness. The beds of tests 1 to 125 inclusive, except tests 52, 53, and 54, were prepared in this way.

Table 5 gives the data and computed results of all the reliable tests made on the passage of air through beds of shot.

Pressure A was taken above the upper (standard) bed, and pressure B between the upper and lower beds. Pressures denoted by + signs were obtained when air was forced from the measuring tank through the apparatus, and pressures denoted by − signs when air was flowing through the apparatus into the tank.

TABLE 5.—*Experiments on the flow of air through two consecutive beds of shot.*

BOTH BEDS OF SHOT REMOVED, LEAVING ONLY THE SCREENS AND THEIR SUPPORTS.

No. of test.	Length of test.	Total air.	Air per minute.	Temperature of air.	Pressures + or −	Pressure A (over upper bed).	Pressure B (between beds).	Pressure A minus pressure B.	Square root of pressure A.	Square root of pressure B.	Square root of pressure A minus pressure B.
	Min.	*Pounds.*	*Pounds.*	° *F.*		*Inches.*	*Inches.*				
1	0.70	0.738	1.054	65	+	0.19	0.105	0.085	0.436	0.324	0.291

LOWER BED 0.5 INCH THICK, OF SHOT OF MEAN DIAMETER OF 0.0974 INCH.

2	3.533	0.765	0.2165	64	−	1.34	0.53	0.81	1.157	0.727	0.90
3	3.033	.752	.248	64	+	1.60	.775	.825	1.266	.880	.907
4	1.967	.741	.377	64	+	3.32	1.49	1.83	1.82	1.22	1.352
5	1.783	.765	.429	65	−	4.68	1.90	2.78	2.16	1.377	1.666
6	1.333	.735	.552	65	+	6.27	2.73	3.54	2.502	1.651	1.88
7	1.333	.765	.574	65	−	7.10	3.10	4.00	2.763	1.758	2.00
8	.967	.735	.760	65	+	10.97	5.00	5.97	3.31	2.234	2.442

LOWER BED 0.75 INCH THICK, OF SHOT OF MEAN DIAMETER OF 0.0974 INCH.

9	3.867	0.746	0.193	68	+	1.41	0.77	0.64	1.187	0.877	0.80
10	2.45	.7578	.309	69	−	3.19	1.51	1.68	1.785	1.227	1.295
11	1.917	.746	.389	69	+	4.51	2.30	2.21	2.13	1.52	1.485
12	1.917	.758	.385	69	−	5.05	2.37	2.68	2.24	1.54	1.636
13	1.45	.739	.510	69	+	7.23	3.63	3.60	2.69	1.90	1.90
14	1.517	.758	.500	73	−	8.47	4.03	4.44	2.91	2.01	2.11
15	1.467	.758	.517	74	−	8.56	4.06	4.50	2.92	2.01	2.12
16	4.617	.758	.164	74	−	1.12	.53	.59	1.06	.73	.769
17	1.167	.740	.634	74	+	10.97	5.47	5.50	3.32	2.34	2.34
18	1.10	.7275	.661	70	+	11.65	5.95	5.70	3.41	2.44	2.38

LOWER BED 1.125 INCHES THICK, OF SHOT OF MEAN DIAMETER OF 0.0974 INCH.

19	4.533	0.758	0.167	74	−	1.43	0.80	0.63	1.195	0.893	0.793
20	3.133	.752	.240	74	+	2.52	1.53	.99	1.587	1.237	.994
21	2.333	.740	.3175	72	+	3.79	2.24	1.55	1.945	1.497	1.243
22	2.250	.758	.337	73	−	4.64	2.59	2.05	2.15	1.61	1.43
23	1.833	.746	.407	73	+	6.50	3.81	2.69	2.546	1.950	1.638
24	1.700	.758	.446	73	−	7.61	4.51	3.10	2.756	2.122	1.758
25	1.550	.758	.489	73	−	9.17	5.46	3.71	2.680	2.335	1.924
26	1.250	.728	.582	71	+	11.80	7.05	4.75	3.432	2.653	2.175

LOWER BED 1.50 INCHES THICK, OF SHOT OF MEAN DIAMETER OF 0.0974 INCH.

27	5.450	0.7515	0.138	70	+	1.36	0.91	0.45	1.165	0.953	0.670
28	4.400	.758	.172	70	−	1.86	1.18	.68	1.363	1.086	.825
29	2.950	.746	.253	69	+	3.56	2.33	1.23	1.886	1.525	1.108
30	2.550	.7575	.297	69	−	4.66	2.93	1.73	2.157	1.710	1.314
31	2.233	.758	.339	69	−	5.93	3.72	2.21	2.433	1.927	1.485
32	2.050	.7575	.369	69	−	7.07	4.44	2.64	2.660	2.106	1.623
33	1.733	.733	.422	67	+	8.21	5.38	2.83	2.863	2.317	1.681
34	1.767	.758	.429	68	−	9.75	6.16	3.59	3.120	2.480	1.893
35	1.417	.734	.517	68	+	11.90	7.85	4.05	3.447	2.800	2.012

LOWER BED 2.25 INCHES THICK, OF SHOT OF MEAN DIAMETER OF 0.0974 INCH.

36	6.367	0.754	0.1185	70	−	1.37	1.00	0.37	1.170	1.00	0.608
37	4.217	.7335	.173	67	+	2.51	1.92	.59	1.583	1.384	.768
38	3.500	.737	.211	70	+	3.49	2.66	.83	1.866	1.630	.910
39	2.900	.758	.261	67	−	4.85	3.57	1.28	2.200	1.888	1.131
40	2.450	.754	.308	69	−	6.60	4.87	1.73	2.567	2.205	1.314
41	2.050	.737	.359	68	+	8.20	6.26	1.94	2.860	2.501	1.392
42	2.067	.755	.365	68	−	9.02	6.67	2.35	3.01	2.58	1.532
43	1.667	.730	.438	69	+	11.76	9.00	2.76	3.426	3.000	1.660

Table 5.—*Experiments on the flow of air through two consecutive beds of shot*—Cont'd.

LOWER BED 3 INCHES THICK, OF SHOT OF MEAN DIAMETER OF 0.0974 INCH.

No. of test.	Length of test.	Total air.	Air per minute.	Temperature of air.	Pressures + or −	Pressure A (over upper bed)	Pressure B (between beds).	Pressure A minus pressure B	Square root of pressure A.	Square root of pressure B	Square root of pressure A minus pressure B
	Min.	*Pounds.*	*Pounds.*	*° F.*		*Inches.*	*Inches.*				
44	8.133	0.751	0.0923	65	+	1.19	0.975	2.15	1.091	0.986	0.463
45	5.467	.763	.1394	66	−	2.11	1.67	.44	1.453	1.292	.663
46	4.217	.751	.178	65	+	3.22	2.58	.64	1.793	1.606	.800
47	3.333	.763	.229	65	−	4.74	3.75	.99	2.176	1.936	.994
48	2.417	.732	.303	66	+	7.54	6.135	1.405	2.744	2.474	1.184
49	2.300	.763	.332	66	−	8.73	6.85	1.88	2.955	2.616	1.370
50	2.100	.763	.363	66	−	10.76	8.25	2.51	3.277	2.870	1.583
51	1.833	.733	.400	66	+	11.90	9.66	2.24	3.447	3.105	1.495

LOWER BED 3.16 INCHES THICK, OF SHOT OF MEAN DIAMETER OF 0.0974 INCH.

The same identical shot balls were used for tests 44 to 51, inclusive, as for tests 52 to 54, inclusive; but before making the latter three the lower bed of shot was loosened by turning down and up several times, and the loosening was accompanied by an increase in the total thickness from 3 inches to 3.16 inches.

No. of test.	Length of test.	Total air.	Air per minute.	Temperature of air.	Pressures + or −	Pressure A (over upper bed)	Pressure B (between beds).	Pressure A minus pressure B	Square root of pressure A.	Square root of pressure B	Square root of pressure A minus pressure B
52	5.233	0.744	0.142	67	−	1.827	1.327	0.500	1.351	1.151	0.707
53	2.433	.744	.306	67	+	5.75	4.36	1.39	2.396	2.086	1.178
54	1.866	.744	.399	67	+	9.65	7.32	2.33	3.104	2.704	1.525

LOWER BED 3.75 INCHES THICK, OF SHOT OF MEAN DIAMETER OF 0.0974 INCH.

No. of test.	Length of test.	Total air.	Air per minute.	Temperature of air.	Pressures + or −	Pressure A (over upper bed)	Pressure B (between beds).	Pressure A minus pressure B	Square root of pressure A.	Square root of pressure B	Square root of pressure A minus pressure B
55	9.633	0.765	0.0794	64	−	1.13	0.949	0.181	1.062	0.973	0.425
56	7.333	.765	.104	64	+	1.560	1.330	.230	1.248	1.151	.429
57	5.966	.765	.128	64	−	2.150	1.820	.330	1.465	1.348	.574
58	4.634	.759	.164	64	+	3.140	2.690	.450	1.770	1.638	.671
59	3.950	.765	.194	64	−	4.230	3.480	.750	2.055	1.863	.865
60	2.734	.759	.278	63	+	7.320	6.340	.980	2.704	2.516	.989
61	2.617	.765	.292	64	−	8.130	6.660	1.470	2.850	2.579	1.212
62	2.383	.747	.313	64	+	9.080	7.700	1.380	3.008	2.774	1.174
63	2.250	.765	.340	64	−	10.50	8.79	1.71	3.24	2.963	1.307
64	2.020	.741	.367	64	+	11.70	9.84	1.86	3.417	3.135	1.363

LOWER BED 4.50 INCHES THICK, OF SHOT OF MEAN DIAMETER OF 0.0974 INCH.

No. of test.	Length of test.	Total air.	Air per minute.	Temperature of air.	Pressures + or −	Pressure A (over upper bed)	Pressure B (between beds).	Pressure A minus pressure B	Square root of pressure A.	Square root of pressure B	Square root of pressure A minus pressure B
65	10.700	0.765	0.0715	64	−	1.040	0.890	0.150	1.020	0.942	0.387
66	7.333	.759	.1035	64	+	1.85	1.65	.20	1.360	1.283	.447
67	5.333	.765	.1435	64	−	2.87	2.74	.13	1.692	1.654	.360
68	4.150	.759	.183	64	+	4.42	3.83	.59	2.101	1.956	.767
69	3.350	.765	.228	64	−	6.28	5.39	.89	2.505	2.322	.942
70	3.020	.759	.2513	64	+	7.20	6.30	.90	2.685	2.508	.947
71	2.917	.759	.260	64	+	7.52	6.63	.89	2.740	2.574	.942
72	2.550	.765	.300	64	−	10.53	8.85	1.68	3.244	2.974	1.295
73	2.450	.765	.312	64	−	10.56	9.00	1.56	3.246	3.000	1.248
74	2.350	.759	.323	63	+	11.08	9.70	1.38	3.326	3.113	1.174

LOWER BED 1 INCH THICK, OF SHOT OF MEAN DIAMETER OF 0.125 INCH.

No. of test.	Length of test.	Total air.	Air per minute.	Temperature of air.	Pressures + or −	Pressure A (over upper bed)	Pressure B (between beds).	Pressure A minus pressure B	Square root of pressure A.	Square root of pressure B	Square root of pressure A minus pressure B
75	4.500	0.766	0.170	63	−	1.055	0.422	0.633	1.027	0.649	0.745
76	3.383	.755	.223	62	+	1.525	.710	.815	1.234	.842	.902
77	2.583	.766	.297	62	−	2.61	1.155	1.455	1.614	1.074	1.206
78	2.133	.754	.3534	62	+	3.49	1.58	1.91	1.867	1.256	1.382
79	1.783	.766	.429	63	−	4.99	2.16	2.83	2.234	1.468	1.681
80	1.500	.738	.492	64	+	6.42	2.88	3.54	2.533	1.696	1.880
81	1.483	.767	.517	63	−	7.68	3.38	4.30	2.770	1.837	2.073
82	1.200	.736	.613	64	+	9.03	4.13	4.90	3.004	2.032	2.214
83	1.117	.754	.675	64	+	11.55	5.37	6.18	3.396	2.317	2.485

Table 5.—*Experiments on the flow of air through two consecutive beds of shot*—Cont'd.

LOWER BED 1.50 INCHES THICK, OF SHOT OF MEAN DIAMETER OF 0.125 INCH.

No. of test.	Length of test.	Total air.	Air per minute.	Temperature of air.	Pressures + or −	Pressure A (over upper bed).	Pressure B (between beds).	Pressure A minus pressure B.	Square root of pressure A.	Square root of pressure B.	Square root of pressure A minus pressure B.
	Min.	*Pounds.*	*Pounds.*	° *F.*		*Inches.*	*Inches.*				
84	4.183	0.757	0.181	65	+	1.400	0.806	0.594	1.182	0.897	0.770
85	2.567	.760	.296	66	−	3.240	1.710	1.530	1.798	1.307	1.236
86	2.200	.762	.346	66	−	4.180	2.190	1.990	2.044	1.478	1.409
87	1.667	.757	.454	66	+	6.310	3.540	2.770	2.510	1.880	1.662
88	1.683	.762	.4525	66	−	7.190	3.840	3.350	2.680	1.958	1.828
89	1 450	.762	.525	66	−	9.180	4.910	4.270	3.028	2.214	2.065
90	1.350	.732	.542	66	+	9.400	5.220	4.180	3.064	2.284	2.043
91	1.167	.744	.637	66	+	11.750	6.520	5.230	5.426	2.551	2.285
LOWER BED 2 INCHES THICK, OF SHOT OF MEAN DIAMETER OF 0.125 INCH.											
92	5.950	0.762	0.128	66	−	1.294	0.761	0.533	1.137	0.872	0.730
93	3.233	.744	.230	66	+	2.830	1.810	1.020	1.681	1.344	1.010
94	2.583	.762	.295	66	−	3.900	2.350	1.550	1.973	1.532	1.244
95	2.177	.750	.354	66	+	5.500	3.450	2.050	2.344	1.856	1.430
96	1.867	.762	.408	66	−	6.960	4.290	2.670	2.636	2.070	1.632
97	1.617	.738	.456	66	+	8.300	5.230	3.070	2.880	2.285	1.750
98	1.600	.762	.476	66	−	9.350	5.720	3.630	3.055	2.390	1.903
99	1.216	.732	.602	66	+	11.900	7.530	4.370	3.447	2.743	2.088
LOWER BED 3 INCHES THICK, OF SHOT OF MEAN DIAMETER OF 0.125 INCH.											
100	6.417	0.762	0.119	66	+	1.055	0.811	0.244	1.027	0.900	0.494
101	4.750	.762	160	66	−	1.733	1.214	.519	1.317	1.102	.720
102	3.550	.756	.213	66	+	2.800	2.070	.730	1.673	1.439	.854
103	2.917	.762	.261	66	−	4.050	2.810	1.240	2.012	1.676	1.113
104	2.333	.738	.316	66	+	5.570	4.090	1.480	2.360	2.023	1.216
105	2.133	.762	.357	66	−	6.930	4.870	2.060	2.631	2.206	1.438
106	1.866	.762	.408	66	−	9.100	6.450	2.650	3.015	2.538	1.627
107	1.550	.744	.480	66	+	11.560	8.440	3.120	3.398	2.904	1.765
LOWER BED 4 INCHES THICK, OF SHOT OF MEAN DIAMETER OF 0.125 INCH.											
108	9.000	0.753	0.0837	72	−	0.797	0.597	0.200	0.893	0.772	0.447
109	5.750	.750	.1305	72	+	1.532	1.185	.347	1.237	1.088	.589
110	4.133	.747	.181	71	+	2.670	2.066	.604	1.633	1.437	.777
111	3.300	.753	.228	71	−	4.010	2.980	1.030	2.005	1.725	1.015
112	2.467	.742	.301	71	+	6.136	4.760	1.376	2.477	2.180	1.172
113	2.330	.754	.324	72	−	6.970	5.210	1.760	2.640	2.281	1.326
114	2.217	.736	.332	72	+	7.360	5.740	1 620	2.710	2.395	1.272
115	2.170	.753	.347	72	−	7.890	5.970	1.920	2.808	2.443	1.385
116	2.000	.753	.377	72	−	9.950	7.500	2.450	3.154	2.740	1.565
117	1.833	.736	.402	72	+	9.920	7.820	2.100	3.150	2.796	1.448
118	1.667	.730	.438	71	+	11.800	9.100	2.700	3.434	3.015	1.642
NO LOWER BED OF SHOT, ONLY THE STANDARD UPPER BED.											
119	2.967	0.742	0.250	71	+	1.021	....	1.021	1.011	....	1.011
120	2.167	.754	.348	71	−	2.044	....	2.044	1.429	....	1.429
121	1.583	.725	.458	71	+	3.004	....	3.004	1.732	....	1.732
122	1.367	.754	.551	71	−	3.840	....	3.840	1.958	....	1.958
123	1.283	.754	.587	71	−	4.530	....	4.530	2.128	....	2.128
124	1.050	.718	.683	71	+	5.250	....	5.250	2.292	....	2.292
125	.800	.718	.898	71	+	8.940	....	8.940	2.990	....	2.990

Figures 8 to 20, inclusive, show graphically the interrelations between the items computed from the test data.

Figures 8 and 9 show the relations between the pressure drops through the lower beds of shot and the weights of air passing through the apparatus, for shot sizes No. 8 and No. 4, respectively. Each curve gives these relations for a constant thickness of the lower shot bed, as indicated on each figure. Points platted as hollow circles are for tests with air flowing from the measuring tank, and points indicated by solid black circles are for tests with the air flowing in the opposite direction. In shape these curves look like parabolas of the form $y^2 = px$, which suggests the approximate law that the weight of air varies directly as the square root of the pressure drop. To test this law, the weights of air were platted with the square roots of the pressure drops. Figure 10 gives the curves thus obtained from experiments in which the lower bed was of No. 8 shot. It appears that for small pressure drops the law holds fairly well, but that for large drops the rate of flow of air is somewhat larger than the law suggests.

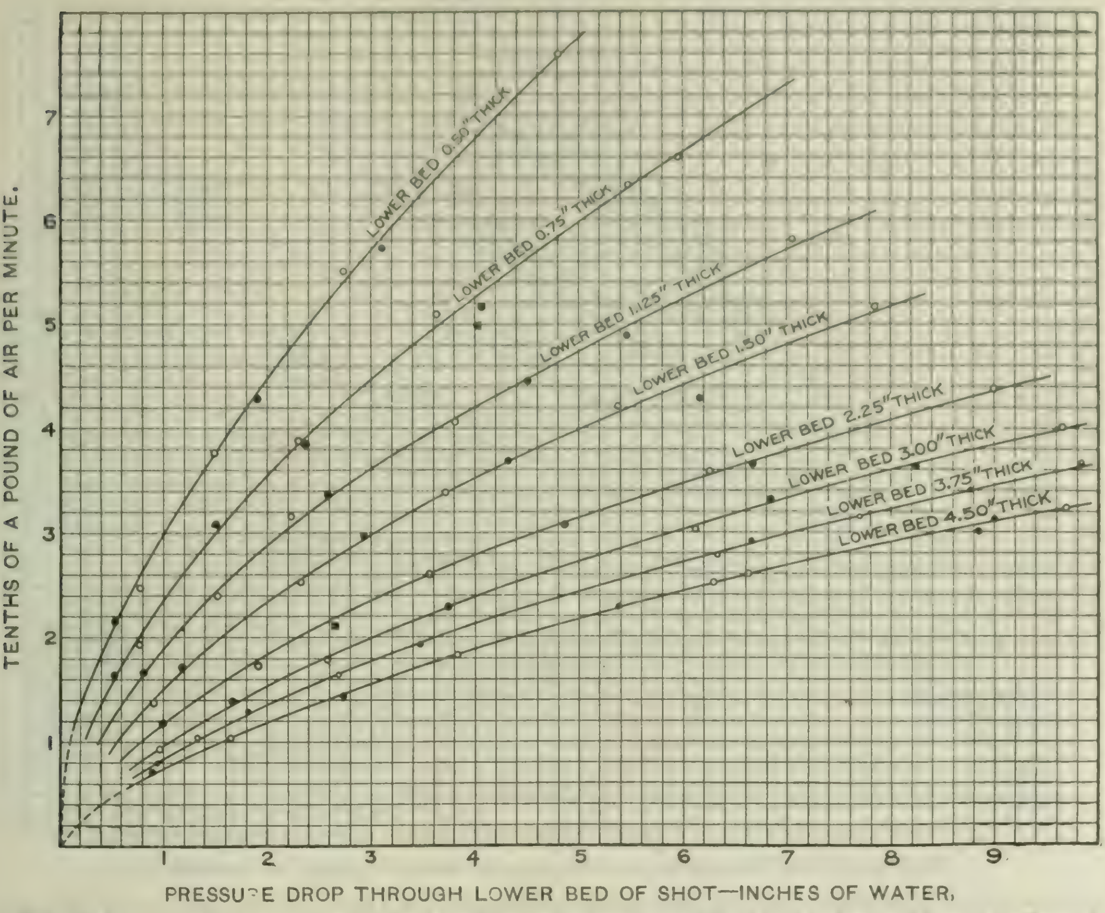

FIG. 8.—Relations between the pressure drops through lower beds of No. 8 shot and rate of flow of air through apparatus. Each curve gives the relation for one thickness of the lower bed, as indicated.

Figures 11 and 12 were platted to show how the thickness of the lower shot bed affects the rate of flow of air through the apparatus at constant pressure drops. The curves show that as the thickness of the lower beds of shot increases, the weight of air passing through the apparatus decreases, very rapidly at first, but as greater thicknesses are reached the rate of decrease gradually diminishes. All curves are asymptotic to the line of zero weight of air when the thickness of the bed of shot is infinite.

Figures 11 and 12 seem to bring out one principle rather strongly, which is that for constant weight of air the ratio of the thickness of the lower shot bed to the pressure drop through the latter is constant.

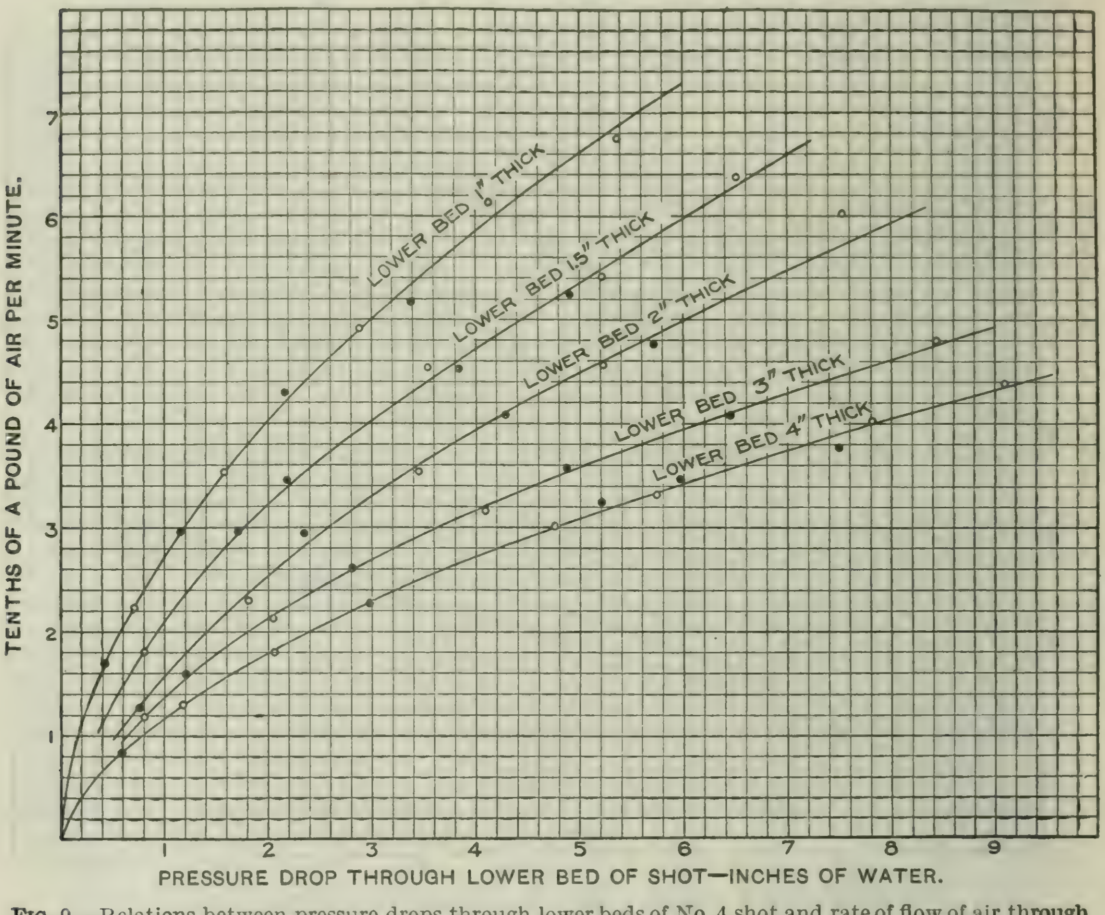

FIG. 9.—Relations between pressure drops through lower beds of No. 4 shot and rate of flow of air through apparatus.

Thus, for example, using figure 11 and taking the constant weight of air passing through the apparatus as 0.2 pound per minute, the pressure drop is about 1.0 inch of water when the lower bed is 1.0 inch thick, 2.0 inches when the lower bed is 2.0 inches thick, 3.0 inches when the lower bed is 3.0 inches thick, and so on. Again, let us take the weight of air passing through the apparatus as constant at 0.45 pound per minute, then we have through the 0.5-inch shot bed a drop of 2 inches of water, through the 1.0-inch bed a drop of 4 inches, and through the 1.5-inch bed a drop of 6 inches, giving a constant ratio of the thickness of the shot bed to the pressure drop of about 0.25. Table 6 gives these ratios for the No. 8 shot for each inch of pressure drop and for every 0.5-inch thickness of the shot bed. In each horizontal row the line headed by A gives the thickness of the lower bed of shot, and the line headed by B gives the ratio of the thickness of the bed to the pressure drop through it. Thus in the first horizontal row the first figure in the line headed by A is 1.55, and the first figure in the line headed by B and given as 1.55 is the ratio of 1.55 to 1.0, the latter value being the pressure drop at the head of the vertical column. In the same manner the second figure of the line headed by A is 3.15; and 3.15 divided by 2.0, the pressure drop given at the head of the second vertical column, is 1.58, which is given in the horizontal line headed by B as the ratio of 3.15 to 2.0. The constancy of the ratios given in the table in each of the horizontal lines headed by B is rather striking, and is apparently more than an accident, because the same constancy of the same ratio is found to exist with the No. 4 shot, as shown in Table 7.

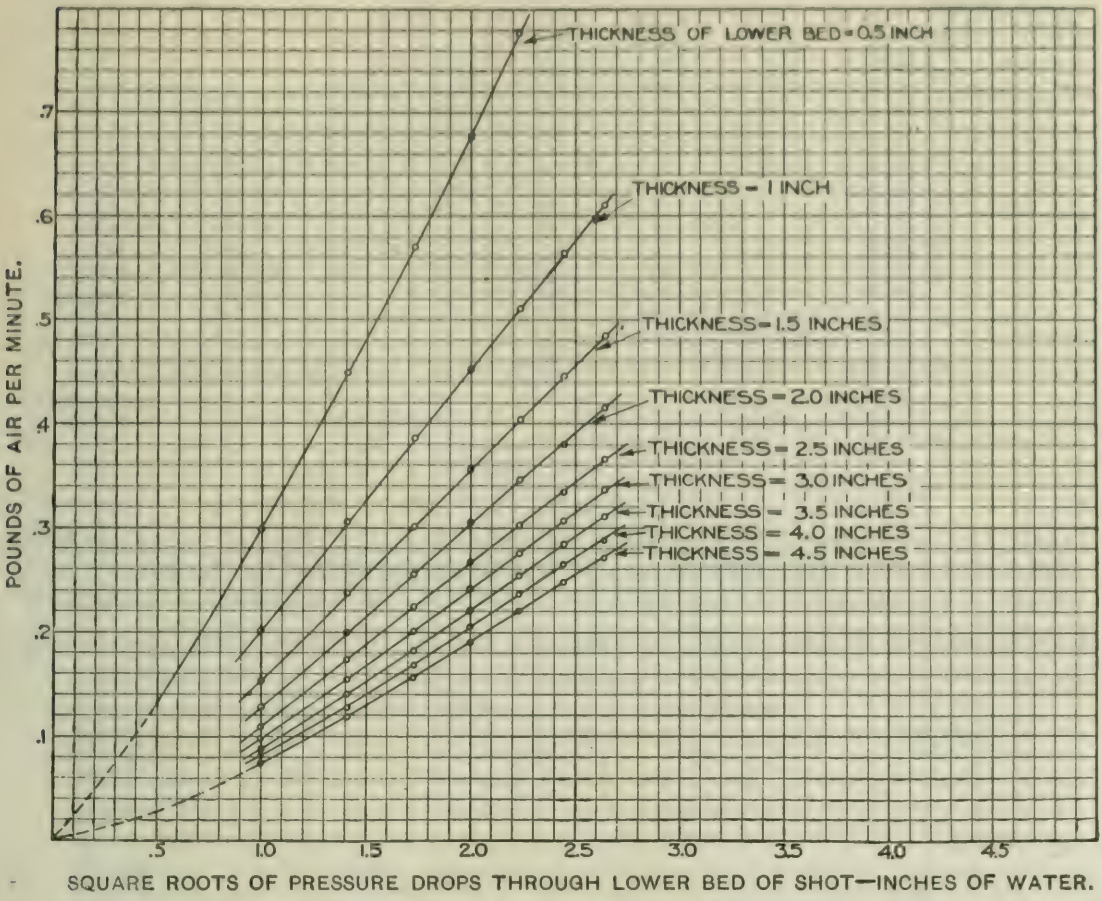

FIG. 10.—Relations between the square roots of the pressure drops through the lower beds of No. 8 shot and the rates of flow of air through the apparatus. Points taken from figure 8.

TABLE 6.—*Computations showing the constancy of the ratio of the thickness of the lower bed of shot to the pressure drop through the lower bed required to deliver a given amount of air per minute for tests in which the lower bed was of shot of mean diameter of 0.0974 inch.*

[Lines headed A give thickness of lower bed in inches; B lines give ratio of thickness to pressure drop.]

Air per minute.	Line.	Pressure drops, in inches of water, through lower bed of shot.						
		1.	2.	3.	4.	5.	6.	7.
Pounds.								
0.15	A	1.55	3.15	....	....	....	....	....
	B	1.55	1.58	....	....	....	....	....
.20	A	1.03	1.99	3.03	4.17	....	....	....
	B	1.03	.99	1.01	1.04	....	....	....
.25	A	.70	1.39	2.07	2.84	3.60	4.44	....
	B	.70	.69	.69	.71	.72	.74	....
.30	A	.49	1.04	1.51	2.05	2.55	3.15	3.73
	B	.49	.52	.50	.51	.51	.53	.53
.35	A	....	.77	1.17	1.55	1.95	2.29	2.77
	B	....	.38	.39	.39	.39	.38	.40
.40	A	....	.61	.93	1.24	1.53	1.83	2.13
	B	....	.30	.31	.31	.31	.30	.30
.45	A	....	.49	.75	1.01	1.25	1.48	1.71
	B	....	.24	.25	.25	.25	.25	.24
.50	A	....	....	.63	.84	1.04	1.24	1.41
	B	....	....	.21	.21	.21	.21	.20
.55	A	....	....	.53	.71	.88	1.06	1.20
	B	....	....	.18	.18	.18	.18	.17
.60	A	....	....	....	.62	.76	.90	1.03
	B	....	....	....	.15	.15	.15	.15
.65	A	....	....	....	.52	.65	.76	.88
	B	....	....	....	.13	.13	.13	.13

TABLE 7.—*Computations showing the constancy of the ratio of the thickness of the lower bed of shot to the pressure drop through the lower bed required to deliver a given amount of air per minute for tests in which lower bed was of shot of mean diameter of 0.125 inch.*

[Lines headed A give thickness of lower bed in inches; B lines give ratio of thickness to pressure drop.]

Air per minute.	Line.	Pressure drops, in inches of water, through lower bed of shot.								
		1.	2.	3.	4.	5.	6.	7.	8.	9.
Pounds.										
0.20	A	1.65	3.25	....	....	....	....	....	....	....
	B	1.65	1.62	....	....	....	....	....	....	....
.25	A	1.16	2.18	3.37	....	....	....	....	....	....
	B	1.16	1.09	1.12	....	....	....	....	....	....
.30	A	....	1.63	2.45	3.30	....	....	....	....	....
	B	....	.81	.82	.82	....	....	....	....	....
.35	A	....	1.28	1.87	2.47	3.10	3.85	....	....	....
	B	....	.64	.62	.62	.62	.64	....	....	....
.40	A	....	1.01	1.50	1.96	2.43	2.94	3.44	4.09	....
	B	....	.50	.50	.49	.49	.49	.49	.51	....
.45	A	....	....	1.23	1.62	2.01	2.40	2.77	3.14	3.55
	B	....	....	.41	.40	.40	40	.40	.39	.40
.50	A	....	....	1.00	1.36	1.69	2.01	2.32	2.65	2.93
	B	....	....	.33	.34	.34	.33	.33	.33	33
.55	A	....	....	....	1.24	1.43	1.72	2.00	2.28	....
	B	....	....	....	.31	.29	.29	.29	.28	....
.60	A	....	....	....	.95	1.22	1.48	1.74	1.97	....
	B	....	....	....	.24	24	.25	.25	.25	....
.65	A	....	....	....	....	1.03	1.28	1.51	....	....
	B	....	....	....	....	.21	.21	.22	....	....

PRACTICAL DEDUCTIONS.

Practical deductions from the above principle can be made as follows:

Other things remaining the same, if the thickness of the fuel bed be doubled the work done by the fan must be about doubled in order that the same weight of air shall pass through the fuel bed per minute.

Since the absolute pressure of the air remains the same within 1 or 2 per cent, the volume of the air remains nearly the same in all cases; hence nearly the same volume of air is displaced against double the pressure by the expenditure of double the work. The same reasoning applies whether the thickness of the fuel bed is doubled or quadrupled.

Further, by likening the bed of shot to the tubes in a water-tube boiler, if the length of the path of the gases among the tubes be doubled while other things remain the same, the fan work required to put the same weight of gases through the boiler is doubled, and so on. This is an important principle, as affecting the arrangement of the heating surface of a boiler. The principles of heat transmission require, for high efficiency in heat absorption, long and narrow gas passages, and the fan work required perhaps increases about directly with the length of the gas passage through the boiler. Fortunately the steam used by a fan is a small portion of that generated, so that there seems to be a chance to improve the economy of steam-boiler operation by judicious use in boiler design of the above principle as applied to both fuel bed and boiler.

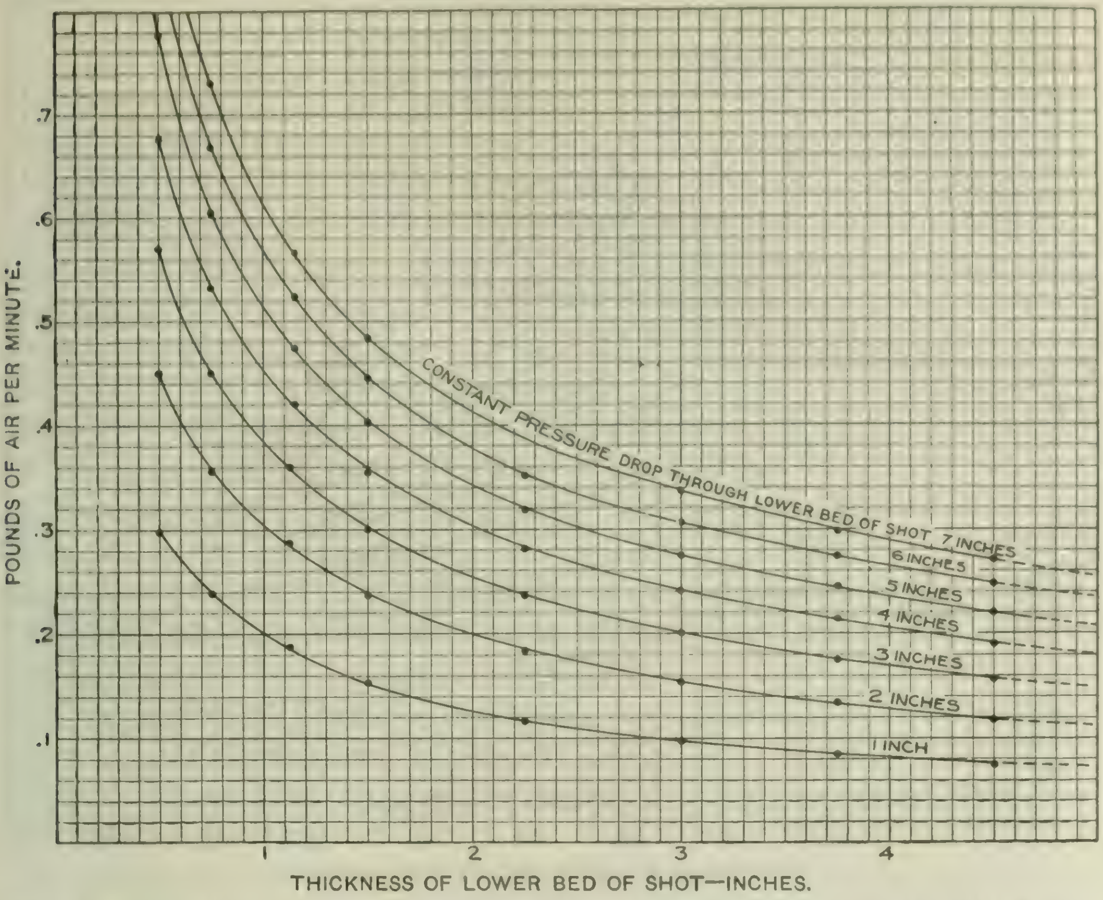

FIG. 11.—Relations between the thickness of the lower beds of No. 8 shot and the rates of flow of air through the apparatus. Each curve shows the relation for one constant pressure drop through the lower bed.

By following any vertical line in figure 11 it is seen that the pressure drop increases faster than the weight of air, although it does not increase quite as the square of the latter. On the average, for constant thickness of the shot bed, to double the weight of air requires that the pressure drop be increased about 3.25 times; to treble it the drop must be increased about 6.00 times. If a similar law holds good for hot gases and in steam boilers, the following practical deduction can be made:

Suppose that it is desired to double or treble the capacity of a plant without making any changes in the furnaces and boilers. Such increases of capacity would require about double and treble the quantities of air to be put through the fuel beds and boilers. As already stated, in order to force through such greater amounts of air the total pressure drops would have to be, respectively, about 3.25 and 6.00 times as large as in the original case; so that in the case of doubled capacity it would be necessary to force twice the weight (volume) of gas against 3.25 times more pressure, which would make the total work required from the fan 2 (volumes) × 3.25 (pressure) = 6.50 times as large as in the original case; and in the case of trebled capacity three times the weight (volume) of air forced against 6.00 times more pressure would make the total work required from the fan

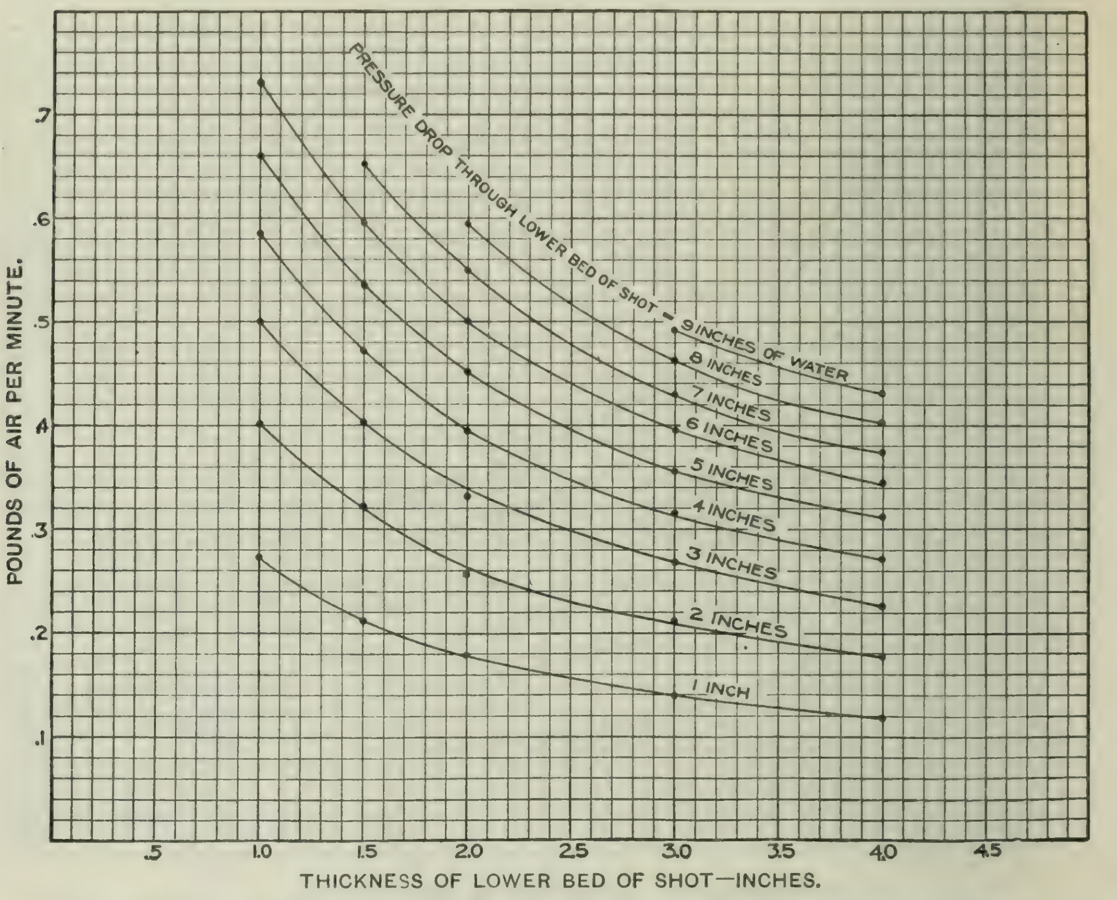

FIG. 12.—Relations between the thickness of the lower beds of No 4 shot and the rates of flow of air through the apparatus. Each curve shows the relation for one constant pressure drop through the lower bed, as indicated on the chart.

3 (volumes) × 6.00 (pressure) = 18.0 times as great as in the original case of ordinary capacity.

If at 100 per cent of rated capacity the plant consumes 2 per cent of the total steam generated in running fans, then when doubling the capacity the steam consumption by the fans will be

$$\frac{2 \text{ per cent} \times 6.5}{2 \text{ (capacity)}} = 6.5 \text{ per cent}$$

and when trebling the capacity the steam consumption by the fans will be

$$\frac{2 \text{ per cent} \times 18}{3 \text{ (capacity)}} = 12 \text{ per cent}$$

of the total steam generated.

It is apparently undesirable to attempt more than a doubling or perhaps trebling of the rate of working of most boilers already installed, unless more efficient fans are designed and used, as they well may be. The mechanical efficiency of most fans now obtainable is probably well under 50 per cent in most cases; some English makes of mine-ventilating fans are up in the seventies, and it is quite likely the reason fans in general are so inefficient is that purchasers demand nothing better or are not willing to pay a somewhat higher price. An increase in grate area will keep the power consumption of the fans from rising as fast as the above calculation indicates. Rebaffling the boilers will often permit the capacity to be doubled or even trebled while still getting more steam than formerly per pound of coal for uses outside the boiler room. It is always to be remembered that the work expended on the gases in driving them through the fuel bed and boiler is partly recovered as heat by the boiler. But the most hope of all lies in the designing of new types of boilers specially fitted for high rates of working.

It is well to bear in mind that fan equipments designed to supply three or four times as much air under several times the pressure would also be provided with more efficient engines, which is an additional factor favoring high-capacity working.

In the cases discussed above of doubling or trebling boiler capacity, somewhat thicker fuel beds would be required, but some locomotive tests given in a succeeding portion of this bulletin show that even then the work required to force the air through the fuel and boiler does not increase any faster than the above calculation indicates. Provided that the boiler proper were such that its efficiency as a heat absorber did not drop much on increasing its rate of working, and that the fuel were such as not easily to be carried up from the bed, such an increase in steam production would be a very sound step commercially. The waste heat of the steam from the fans could be largely recovered in heating the feed water, inasmuch as the auxiliaries of the modern turbine power plant do not ordinarily supply enough steam for this purpose. Best of all, the first cost of the plant would be increased very little, while it would supply two, three, or four times the customary amount of steam. With new boilers properly designed this great increase in capacity need be at no sacrifice in equivalent evaporation.

It may well be asked whether the rate of combustion would keep up with the increased supply of air. At present there are no accurate experimental data at hand to prove that it would, but everyday observations of blast furnaces and blacksmith's forges indicate that the faster the air is blown through the fuel bed the higher is the rate of combustion, the temperature remaining fully as high or increasing. Of course, when increasing the pressure drop through the fuel bed, and consequently the supply of air, the supply of fuel and the thickness of its bed must be regulated and carefully watched. At present too thick a fuel bed is often carried with a comparatively low draft, in the attempt to obtain a high temperature or to reduce the chances of the formation of holes in the fire. The first attempt is questionable as to its soundness and the second is made by lazy firemen. Too thick a fuel bed places needless resistance in the path of the gases. In all attempts to force up the capacity of boilers care must be taken not to have the velocity of air through the fuel bed high enough to carry up fine coal; resort can usually be had to more grate area.

On following any curve of figures 11 and 12 from left to right, it is evident that the weight of air flowing through the apparatus per minute decreases rapidly at first with increasing thickness of the bed of shot, and then more and more slowly. If it is justifiable to reason from beds of shot to water-tube boilers of the cross-flow type (like the Babcock & Wilcox), and perhaps also to the parallel-flow type (like the Heine), it is probable that doubling the height (number of rows of tubes) of the first type and the length of the tubes of the second type will not reduce the weight of gases flowing through the boiler to anything like half, if the pressure drop through the boiler proper remains unchanged.

According to the curves given for the shot, increasing the bed to four times the thickness in certain cases will not quite reduce the weight of gases flowing to one-half; increasing the thickness to nine times will not quite reduce the weight of gases flowing to one-third. This fortunate relation actually seems to hold more or less in the case of small laboratory boilers. In a forthcoming bulletin on heat transmission into boilers, now nearly finished by the present authors, are given data from about 250 tests on small laboratory multitubular boilers fed with air heated electrically. Some interesting results from two boilers of ten tubes each are tabulated below.

Tests from two laboratory multitubular boilers fed with air heated electrically

		Boiler No. 1.	Boiler No. 2.
Internal diameter of tubes.....	inches..	0.175	0.175
Length of tubes...	do....	8.28	16.125
Air passing through boilers per second under a pressure drop of—			
Ten inches of water at an initial temperature of 700° F....	.pounds..	.0096	.0088
Five inches of water at an initial temperature of 700° F....	...do...	.0073	.0067

The longer tubes absorbed about 10 per cent more of the heat available to them from each pound of air than did the shorter ones, and only about 8 per cent less air passed through them, under the same pressure drop. Therefore the longer tubes actually absorbed as much heat total as did the shorter ones, from less air. Taking as 100 per cent the weight of air passing through the shorter tubes, the 92 per cent of air passing through the longer ones is higher than one might expect on the basis of the experiments with shot. One possible explanation is that a considerable part of the resistance to the passage of air through the boiler tubes lies at the entrances to the tubes in some vena-contracta effect.

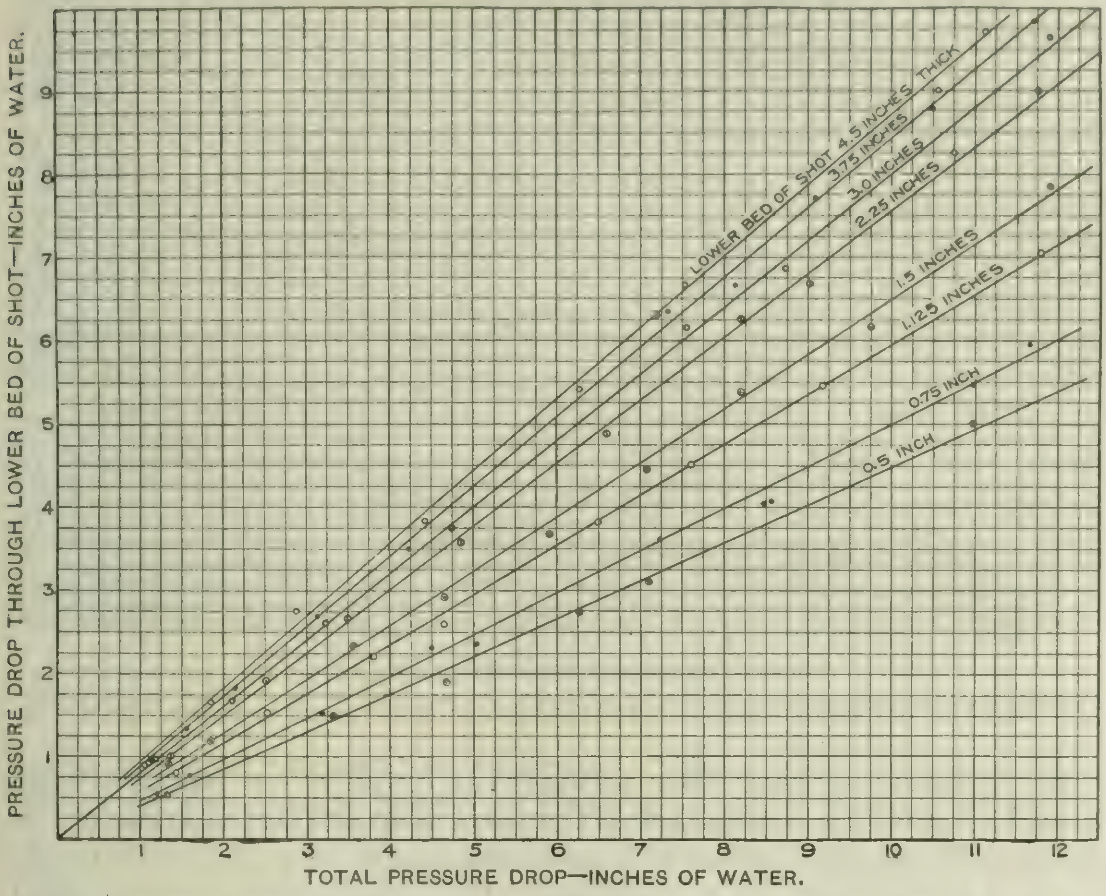

FIG. 13.—Relations between total pressure drops and drops of pressure through lower beds of No. 8 shot.

Figures 13 and 14 show the relation between the total drop through both beds of shot and the drop through the lower bed only. The curves are as nearly straight lines as can be expected, indicating that the ratio of the two pressures is constant and confirming the statement under *a* (p. 11), the same statement having already been confirmed by experiments on large boilers.

Figures 15 and 16 show how the pressure drop through the lower bed increases with the thickness of the bed when the total drop remains constant. Each of the curves gives this relation for a constant total drop, as indicated in the figures. Each curve is asymptotic to the corresponding pressure drop through the lower bed of shot, showing that the latter drop approaches the total drop as the thickness of the lower bed increases. The two pressures would be equal if the thickness of the lower bed were infinite. A similar statement is applied elsewhere in this bulletin (see p. 43) to a steam boiler and its fuel bed.

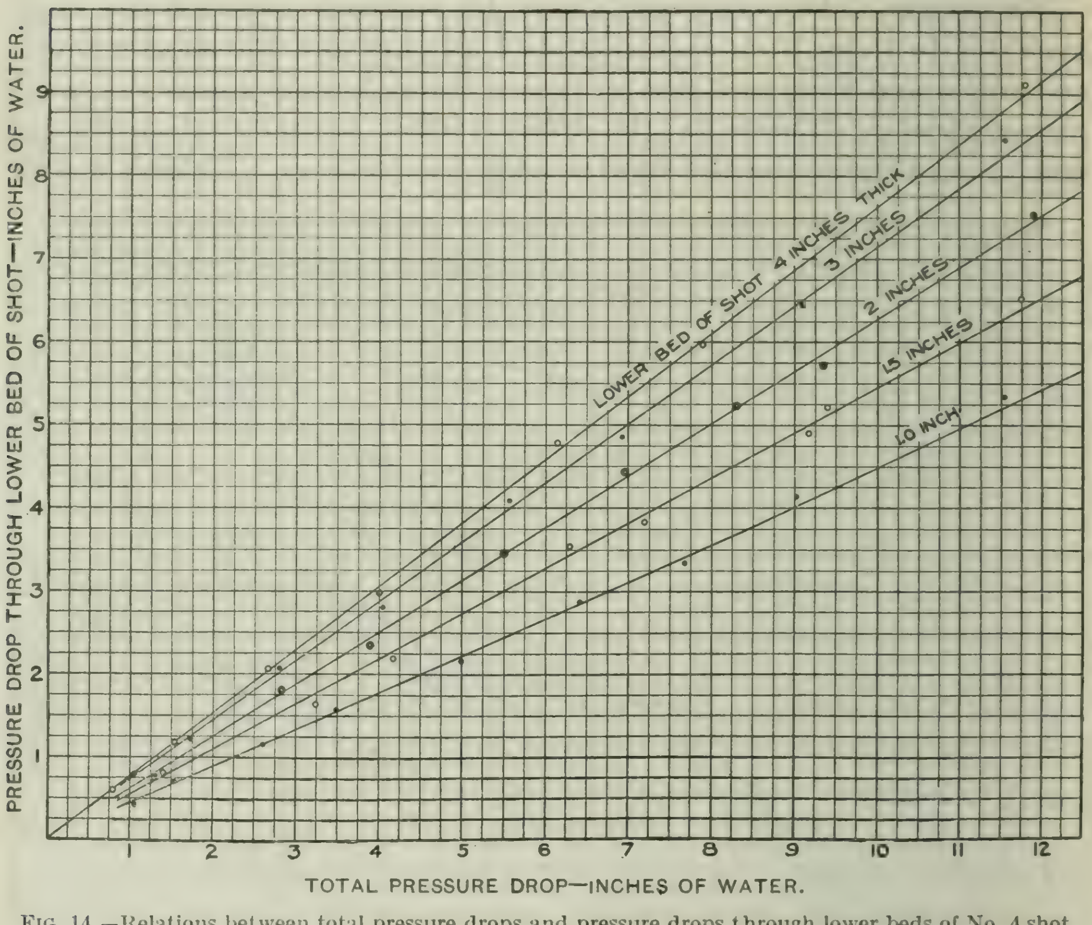

FIG. 14.—Relations between total pressure drops and pressure drops through lower beds of No. 4 shot.

Figures 17 and 18 show the relation between the pressure drop through the lower shot bed and the weight of air passing through the apparatus. Each curve gives the relation for a constant total drop through both beds, as indicated on the figure. The curves show that the weight of air passing through the apparatus decreases as the pressure drop through the lower bed approaches the total drop, and that the weight becomes zero when the two drops are equal. The points at the extreme left were determined by leaving the lower bed of shot out in one set of experiments.

Figures 19 and 20 give the relation between the total drop through the apparatus and the weight of air passing through the latter per minute. Each of the curves gives this relation for a constant pressure drop through the lower bed of shot. The curves are drawn starting from a total pressure drop equal to that through the lower bed. This is done because if there should be no pressure drop through the upper bed of shot, no air would pass through it and therefore none through the apparatus. The curves show that when the drop through the lower bed remains constant the rate of flow of air through the apparatus increases with the total pressure drop. The points for the curve starting from 0 were obtained in a set of tests run with no lower bed.

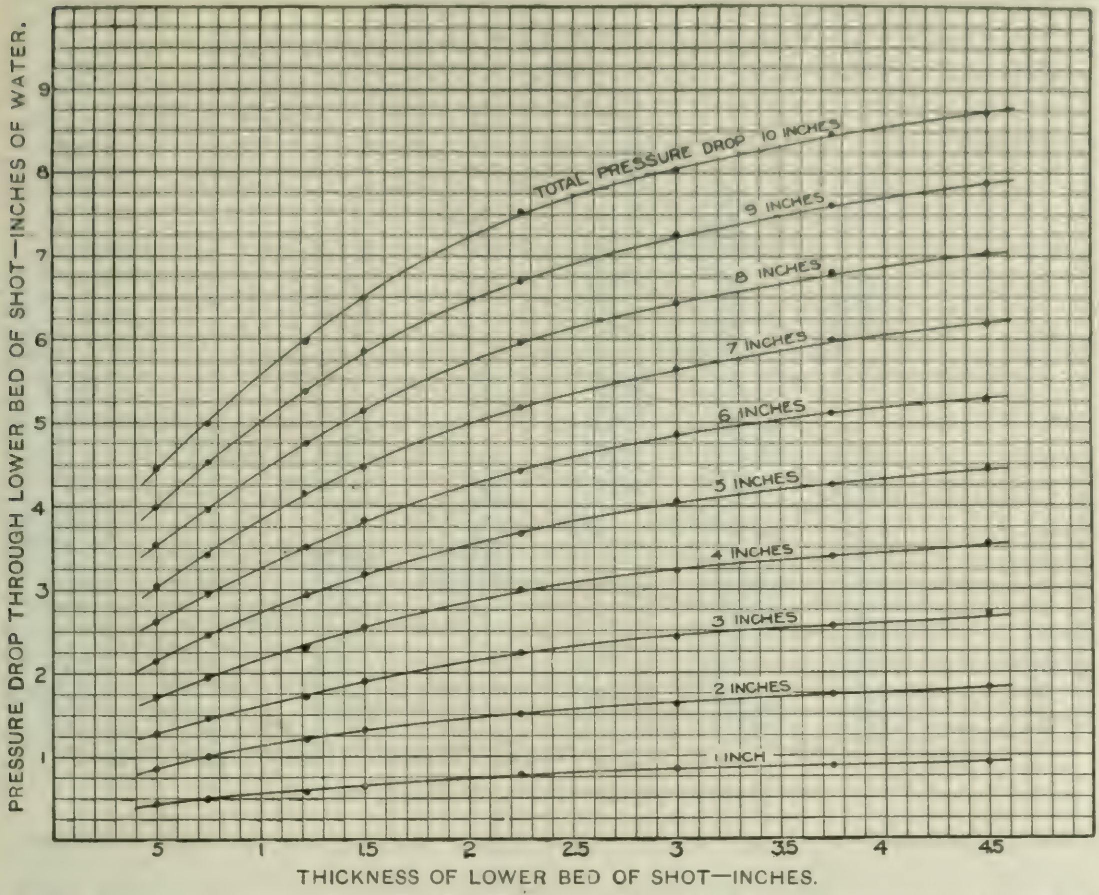

FIG. 15.—Relations between the thickness of the lower bed of No. 8 shot and the pressure drops through it.

From figure 19 the following practical deductions can be drawn:

As the lower bed of shot represents the fuel bed and the upper one the boiler, by analogy we can reason from the showing of the curves that with the same pressure over the fire the weight of gas passing through the boiler will increase with the total pressure drop. Also, by considerations drawn from following any vertical line in figure 19, we may reason that with the total pressure drop constant more gas will flow through the boiler as we cross the curves of lower drops through the fuel bed. This is contrary to what is ordinarily expected by men in charge of boiler rooms. They reason that the higher the pressure drop through the fuel bed the greater the amount of air which will pass through and consequently the higher the rate of combustion; the faultiness of this reasoning lies in its failure to consider also the total pressure drop from ash pit to stack.

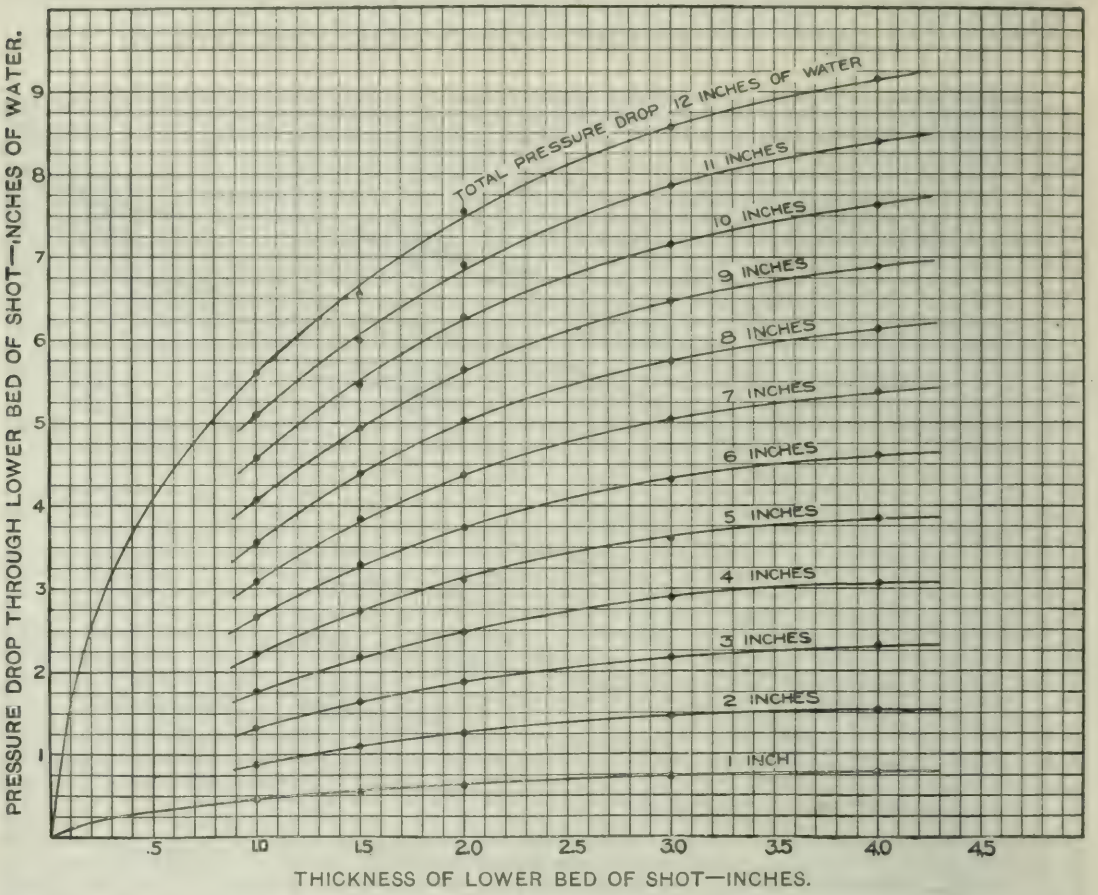

FIG. 16.—Relations between the thickness of the lower bed of No. 4 shot and the pressure drops through it.

RELATION BETWEEN MEAN DIAMETER OF SHOT AND WEIGHT OF AIR PASSING THROUGH THE APPARATUS.

Table 8 gives a comparison of the weights of air passing through the beds of the two sizes of shot. Any horizontal row gives the weight of air and the ratio for the same pressure drops, but for various thicknesses of fuel bed, and any vertical column gives the weights and ratios for the same thickness of beds and various pressure drops. Each horizontal line headed by A gives the weights of air passing through four beds of No. 8 shot; each horizontal line headed by B gives the weights of air passing through beds of No. 4 shot of the same respective thicknesses; figures in the horizontal lines headed by C are the ratios of the two above weights; and figures in the horizontal lines headed by D give the percentage of the variation of each ratio from the average of all the ratios. As shown in the horizontal lines headed by C and D, the ratios of the two weights are nearly constant for all pressures and bed thicknesses, suggesting that the weight of air is a direct function of the diameter of the shot. The average of the ratios of the weights of air is 0.756, and the ratio of the diameters of the large and small shot sizes is 0.779. The two ratios are about the same; whether this is a coincidence is not known; more experiments are needed with several sizes of shot.[a]

TABLE 8.—*Comparison of pounds of air passing through beds of small and large shot under the same conditions.*

Pressure drops through lower beds of shot.	Line.	Thickness in inches, of lower beds of shot.			
		1.	2.	3.	4.
1	A	0.202	0.123	0.098	0.081
	B	.273	.180	.140	.118
	C	.740	.683	.700	.687
	D	−2.0	−9.7	−7.3	−9.1
2	A	.306	.199	154	.128
	B	.402	.262	.211	.178
	C	.761	.760	.729	.719
	D	+ .7	+ .6	−3.4	−4.8
3	A	.385	.256	.200	.168
	B	.500	.335	.268	.226
	C	.770	.764	.747	.743
	D	+2.0	+1.2	−1.2	−1.6
4	A	.452	.305	.241	.204
	B	.585	.394	.315	.271
	C	.772	.774	.765	.752
	D	+2.2	+2.5	+1.3	− .4
5	A	.510	.344	.274	.236
	B	.660	.452	.356	.312
	C	.773	.760	.769	.757
	D	+2.3	+ .6	+1.8	+ .2
6	A	.566	.380	.306	.264
	B	.730	.501	.396	.344
	C	.775	.758	.773	.767
	D	+2.6	+ .3	+2.4	+1.6
7	A	....	.412	.336	.288
	B	....	.550	.430	.374
	C	....	.749	.782	.770
	D	....	− .8	+3.6	+1.9

The practical deduction from the above, as regards the sizes of coal burned under a steam boiler, is that the weight of air passing through a fuel bed increases with the size of the coal, which is in accord with everyday observation. In what way the weight of air depends on the size of coal can not be ascertained from experiments with shot, and even if this relation were determined for one coal such a determination would not be applicable to other coals of different natures. For instance, the shape of the pieces of coal probably has some influence on the flow of air through the bed, and it is a known fact that the pieces of western bituminous coals are in angular shapes, while those of the soft eastern bituminous coals are rounded. The resistance of the coal bed on the grate would also depend somewhat on the manner in which the coal is put onto the grate. Thus the bed will have a different resistance when the coal is shoveled on in hand firing than when it is gradually fed in along with a very gentle agitation, as by a chain-grate stoker, or when fed in and moved along with considerable agitation, as by stokers of the overfeed and the underfeed type. Then, too, the caking of most coals in hot furnaces is constantly changing the resistance to the passage of air.

---

[a] It is interesting to note here that the percentage of voids among spheres is the same whatever their size, if sizes are not mixed. As a check on this conclusion weighings were made of a glass flask filled successively with No. 8 and No. 4 shot; after deducting the weight of the flask the contents weighed the same in the two cases within about 1 per cent.

From the results of the preceding experiments it may be deduced that, since the gas is the carrier of heat, less heat is delivered to the boiler when the resistance through the fuel bed increases, the initial temperature of the gas and total pressure drop remaining the same.

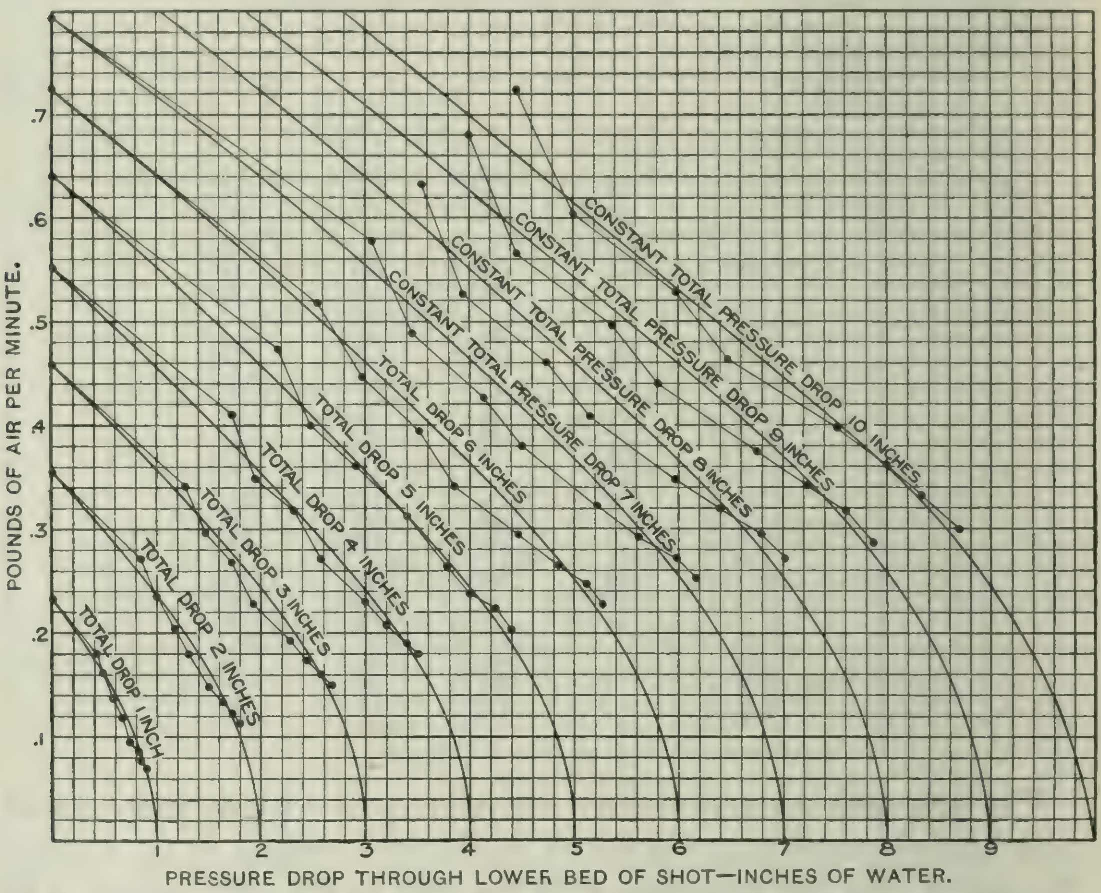

FIG. 17.—Relations between pressure drops through the lower beds of No. 8 shot and rate of flow of air through apparatus for various constant total drops.

With any steam-generating apparatus the resistance to the flow of gases from the fuel bed to the uptake is very nearly constant, and perhaps is affected only by the quantity of soot and ashes on the heating surface. This constant resistance is fixed when the setting is put up and the baffles are inserted in the boiler. The only resistance which varies through a considerable range is that of the fuel bed. An unusually high pressure drop through the grate and fuel bed is an indication of unduly high resistance.

The pressure drop through the fuel bed is often looked upon as so much "draft" available for the burning of coal; and it is widely believed that with any one apparatus the higher the drop through the fuel bed (the "draft" in the furnace), regardless of the total pressure drop, the higher the rate of combustion and the higher the capacity developed.

An application of the principles developed by the experiments on shot beds shows that this almost prevalent belief results from incomplete views of things. The pressure drop through the fuel bed is rather an indication of the resistance which the fuel bed and grate offer to the passage of air, and in judging the rate of working this drop should always be considered in connection with the total drop from ash pit to uptake. With the same total pressure drop the drop through the fuel bed can be made to equal any quantity from nearly zero to the total drop by changing the resistance of the fuel bed only. If the air passages of the grate and all other openings into the furnace were entirely stopped, the pressure drop from ash pit to furnace would be equal to the total pressure drop. In other words, if the resistance to the flow of air from ash pit to furnace were made infinite the pressure above the grate would be the same as in the uptake. On the other hand, with the ash-pit doors fully open and with a bare

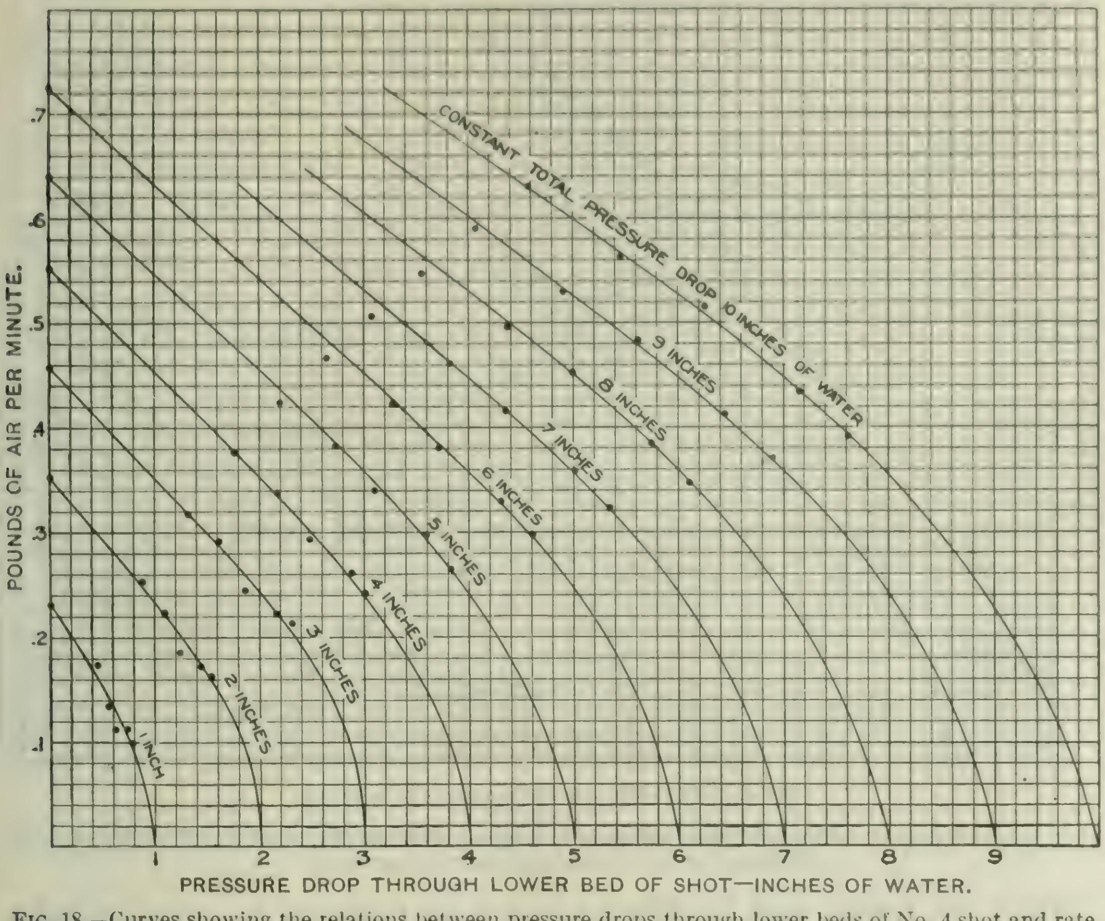

FIG. 18.—Curves showing the relations between pressure drops through lower beds of No. 4 shot and rate of flow of air through apparatus for various constant total pressure drops.

grate having large air passages, the pressure in the furnace would be close to the pressure in the ash pit, or to that of the outside atmosphere; that is, by making the resistance from ash pit to furnace nearly zero the drop of pressure through the grate would be nearly zero. By similar reasoning it could be shown that by decreasing the resistance to the flow of gas from over the fuel bed to the uptake, the pressure drop between these two points could be decreased and that between the ash pit and furnace increased. However, the resistance from furnace to uptake is fixed by the design and construction of the boiler, and therefore can not be changed by manipulation or by the quantity of the coal; for this reason it is not given more detailed consideration in this bulletin.

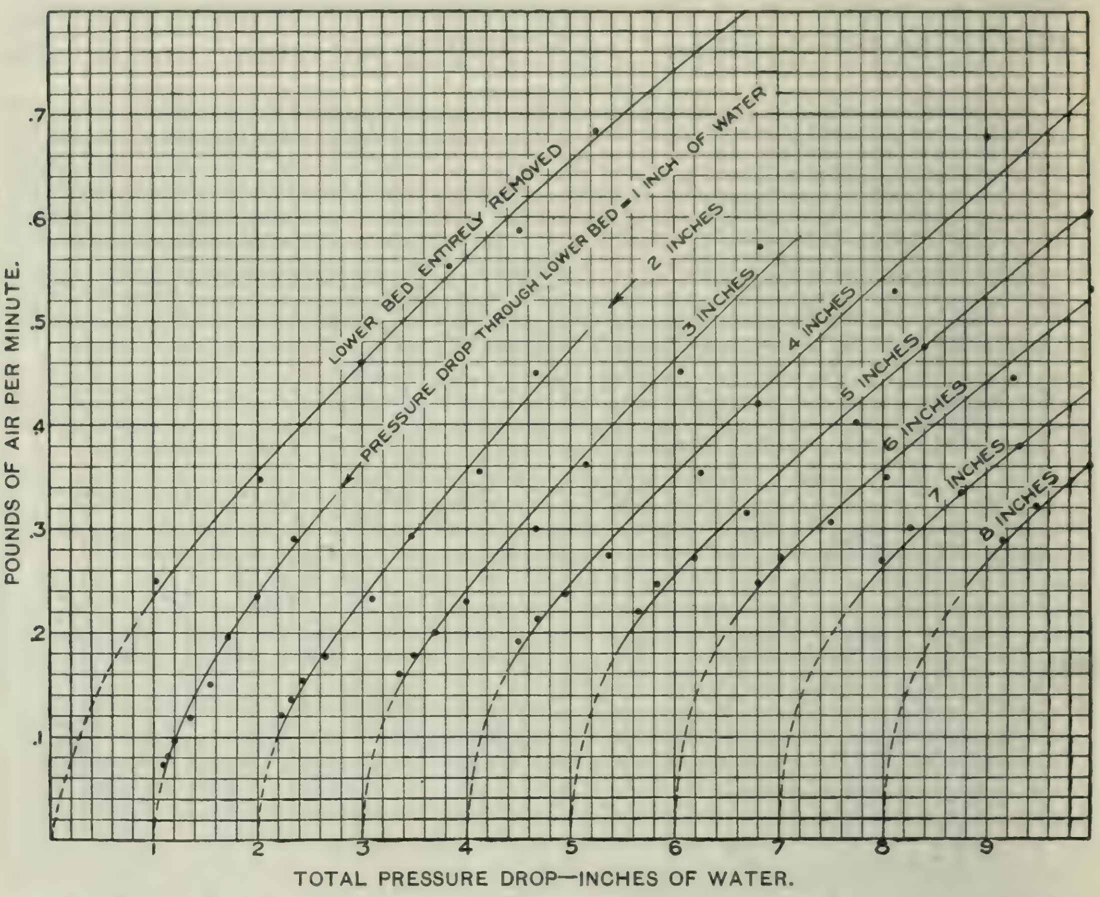

FIG. 19.—Relations between total pressure drops and rate of flow of air through apparatus for several constant pressure drops through lower beds of No. 8 shot.

EFFECT OF PRESSURE DROP THROUGH THE FUEL BED ON RATE OF COMBUSTION AND ON EVAPORATION.

Since for any one steam-generating apparatus the resistance to the flow of gas between the furnace and the uptake is practically constant, it is reasonable to expect that for a greater difference in pressures between these two places a greater weight of gases will pass through the boiler, provided that the temperature of the gases remains unchanged. The passage of a greater weight of gases at the same temperature is the accompaniment of a higher rate of combustion and the cause of a more rapid production of steam. Thus we may logically expect that the rate of combustion and the capacity of the boiler will vary somewhat with the difference of pressures between the furnace and the uptake.

The resistance which the fuel bed offers to the flow of air varies with the thickness of the fire, the size of the coal, and probably with the moisture of the coal and the nature and quantity of ash on the grate. It would hardly be reasonable to expect increased rate of combustion and higher capacity when one or more of these factors increases the resistance of the fuel bed, although the pressure drop from ash pit to furnace be thereby increased. The resistance caused by these factors can be changed by manipulation of the fuel bed.

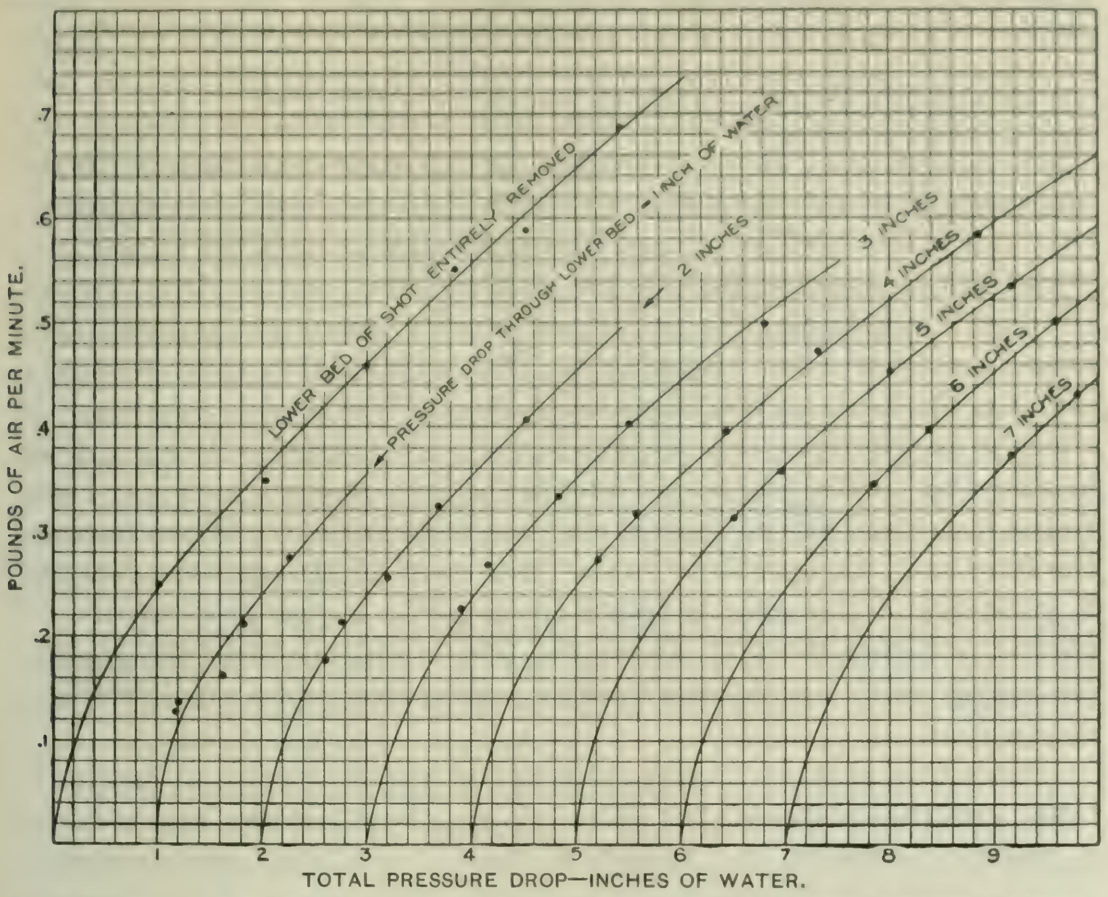

FIG. 20.—Relations between total pressure drops and rate of flow of air through apparatus for several constant pressure drops through lower beds of No. 4 shot.

The resistance of the grate is constant and should be small, because the energy required to move air through it is uselessly expended. It follows that the percentage of air spaces in the grate should be as high as mechanical construction and factor of safety allow. The pressure drop of air through the grate should be as nearly zero as possible. The power applied to the fans should be utilized as completely as practicable in two ways only—(*a*) in scrubbing ashes and gases of combustion off the solid pieces of fuel, and (*b*) in scrubbing the soot and cooled gases off the water-heating surface.

A pressure ("draft") gage connected to the space above the fuel bed gives useful information as to the condition of the fire to a fireman who understands the significance of its indications. Thus, after cleaning a fire, if the pressure drop from ash pit to fuel bed is too small the fireman may be sure that there are holes in the fire, or that it is too thin; or, if the pressure drop is too great, it is probable that the fire is too thick. A gradual increase of the drop through the fuel bed, after a fire has burned for some time (in case of hand firing especially), is an indication of the accumulation of clinker next the grate. Of course, a drop through the fuel bed is adjudged high or low only after considering it in connection with the total drop through the whole apparatus. It may happen, in the same apparatus, with the same coal from the same bin, and with the same total pressure drop, that much less coal is burned and a smaller amount of steam produced on one day than on another, although the pressure drop through the fuel bed is higher on the day of smaller steam production. The fireman may wonder why this is. The explanation may be drawn out thus from the preceding paragraphs: When coal is taken out of the side and bottom of a bin, the larger pieces tend to flow out first, leaving the smaller pieces and dust in the far corners, which stay there to the last, until all the coarser coal has been burned. When burning the finer coal, the resistance to the passage of air through the fuel bed is greater, and this greater resistance causes a higher pressure drop—that is, a higher "draft" above the fire; simultaneously the smaller air supply results in a lower rate of combustion and a smaller steam production.

Ohm's law is much better understood among electrical engineers than are the above-stated laws of gas flow among steam-boiler engineers; probably the reason is that in electrical measurements the units of drop of potential, resistance, and rate of flow of energy are all named, and the existence of names makes measurements much easier than in the case of the analogous quantities in problems relating to the flow of gases. The well-defined electrical units enable their users to think much more accurately than do the men who have inherited, from times when science was hardly existent, such vague ideas as that of "draft."

The following statements are general:

(*a*) If in any one steam-generating apparatus the total pressure drop and the temperature of furnace gases remain constant, the weight of gases passing through the apparatus per unit of time varies inversely as the total resistance. Since in the same apparatus only the resistance of the fuel bed is changeable, it may be said that under the above circumstances the weight of gases passing through the apparatus per unit of time varies inversely as the resistance of the fuel bed; therefore it varies also inversely as some power of the pressure drop through the fuel bed.

(*b*) In any one apparatus the resistance to the flow of gases through the combustion chamber and boiler remains constant, and therefore with constant temperature of the gases the weight passing through per unit of time is proportional to some power of the pressure drop through the combustion chamber and boiler.

STEAMING TESTS BY THE GEOLOGICAL SURVEY AT ST. LOUIS, MO.

As a test of the soundness of the reasoning in the preceding paragraphs, tests 140 to 434, inclusive, made at the Geological Survey's fuel-testing plant at St. Louis, Mo., were classified in various groupings according to gaseous pressure drops ("drafts"), and the results were platted in the charts reproduced as figures 21 to 24.

The boilers were of the standard hand-fired Heine type, not fitted with pressure or exhaust fans, but with steel chimneys. The two boilers and their settings were exactly alike.[a]

The pressures in the furnace were taken in the middle of the length of the grate and about 20 inches above its surface. The pressure in the uptake was taken in the hood at the base of the stack, about 2 feet below the damper and 3 feet above the point of exit of the gases from the boiler proper.

The points given in the charts are not individual tests, but each is an arithmetic average of a number of tests. The figures in any small circle indicate the number of tests averaged to get the points lying on that particular vertical line.

The efficiency 72* used in these charts is the ratio of the heat absorbed by the boiler to the heat of the combustible ascending from the grate. The designation 72* refers to that item of the Government reports of the steaming tests made at the Survey's fuel-testing plant.[b]

Curve 1 of figure 21 is the product of pounds of dry coal burned per square foot of grate per hour and pounds of dry chimney gases per pound of "combustible."[c] Considering that a large number of tests were used in the compilation of this chart, the product just mentioned is very nearly proportional to the weight of gases passing through the boiler per hour. The indication of curve 1 is that this latter weight increases steadily with the increase of drop of pressure through the boiler. Curves 2 and 3 show that the rate of combustion and the capacity rise decidedly with this difference of pressures.

---

[a] For detailed description see Bull. U. S. Geol. Survey No. 325, 1907, p. 173.

[b] For discussion see Bull. U. S. Geol. Survey No. 325, 1907, p. 137.

[c] In this bulletin quotation marks inclose the word "combustible" when it is loosely used to mean "coal free from moisture and ash."

Curve 4 is rather irregular, however; the general indication seems to be that more air is used to burn 1 pound of "combustible" as the difference of pressures becomes larger. This increase in the amount of air is partly due to increased leakage through the boiler setting.

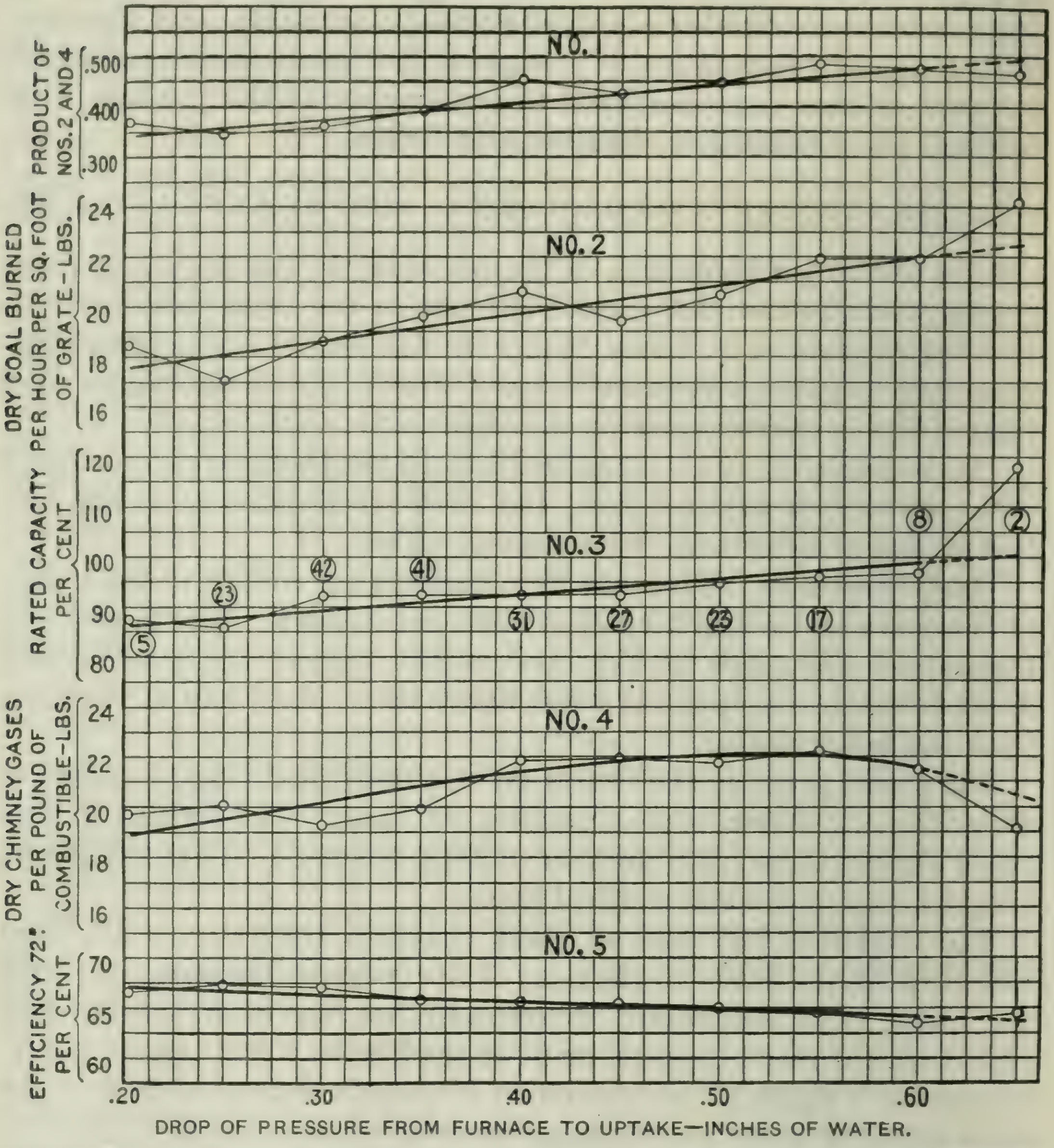

FIG. 21. Relations between pressure drop through two boilers and several items. Curve 1, pounds of coal burned per square foot of grate area per hour times the weight of dry chimney gases per pound of "combustible;" curve 2, pounds of dry coal burned per square foot of grate area per hour; curve 3, percentage of rated capacity developed; curve 4, pounds of dry chimney gases per pound of "combustible;" curve 5, over-all efficiency of grate, furnace, and boiler—that is, from coal to steam (efficiency 72*). In platting these curves all tests were used, the classification being simply on the basis of pressure drop through the boiler.

It may also be the case that among the tests with the higher pressure differences coals high in ash or slow-burning coals predominate, in which case high pressure differences were necessary to obtain rating, and consequently more air entered the furnace through cracks and holes in the fuel bed.

Curve 5 shows that the efficiency drops slightly as the difference of pressures increases. This drop of efficiency can be partly accounted for on the ground that the rate of combustion and the capacity increase. As the former increases more gases leave the fuel bed, with the result that they must pass faster through the combustion space and be afforded less time in which to burn; hence the combustion is less complete. Also, with higher capacity, in order that more heat may be conducted through the heating plates the temperature difference between the dry and wet surfaces must be

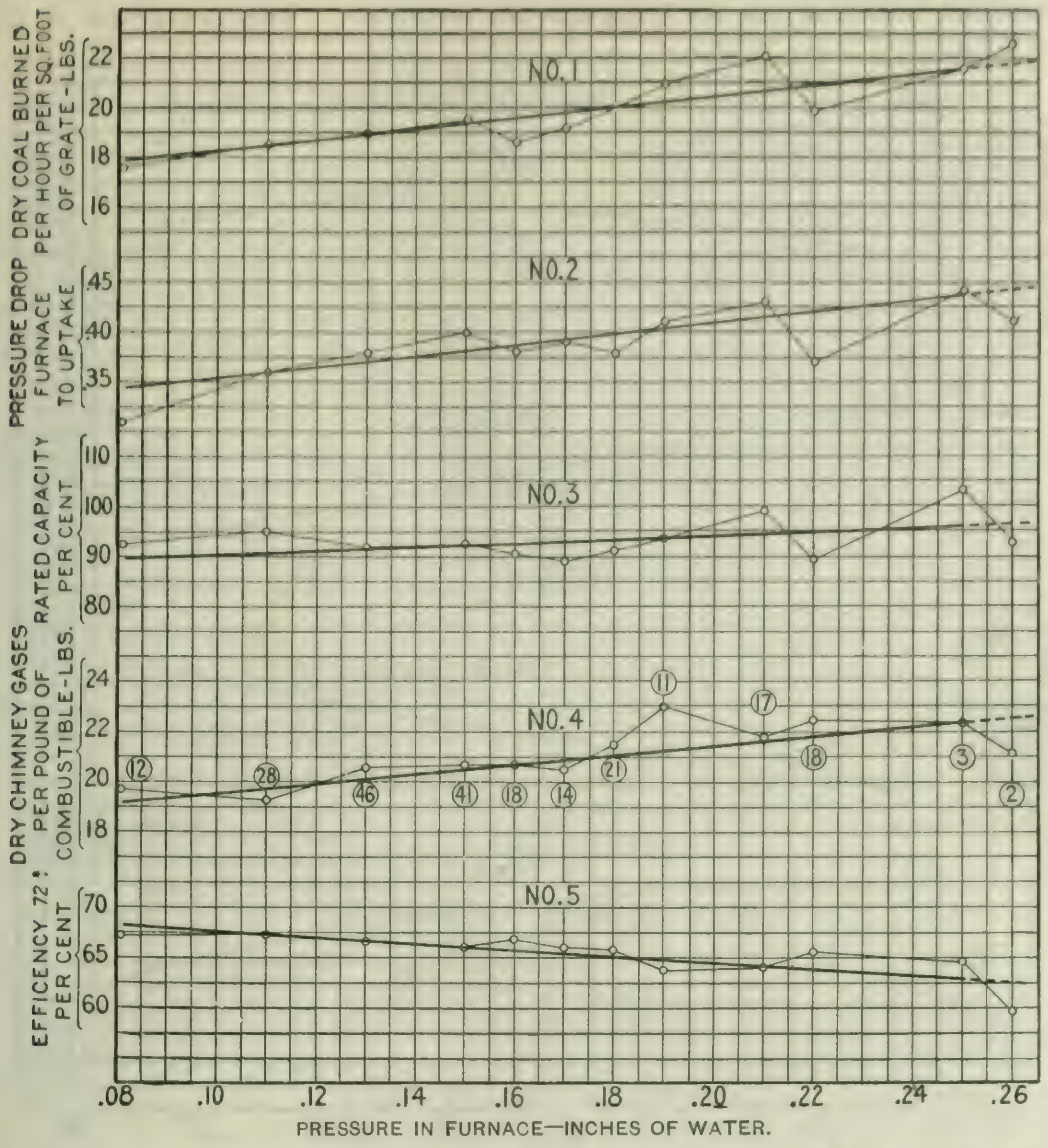

FIG. 22.—Relations between pressure drops through two fuel beds and several items, with varying pressure drops through boilers. Curve 1, pounds of dry coal burned per hour per square foot of grate surface; curve 2, total drop of gas pressure from furnace to uptake; curve 3, rated capacity of boiler developed, per cent; curve 4, pounds of dry chimney gases per pound of "combustible;" curve 5. over-all efficiency (72*), per cent. In platting these curves all tests were used, the classification being simply on the basis of the pressure drop through the fuel bed.

greater. As the temperature of the boiler water remains the same, that of the wet surface of the heating plate can not be lowered. The only way, then, by which the temperature difference can be increased is by raising the temperature of the dry surface. It is this dry surface which receives heat from the gases, and therefore the latter leave the surface hotter when its temperature is higher. The net result is a slightly lower proportionate heat absorption by the boiler when the capacity is higher.

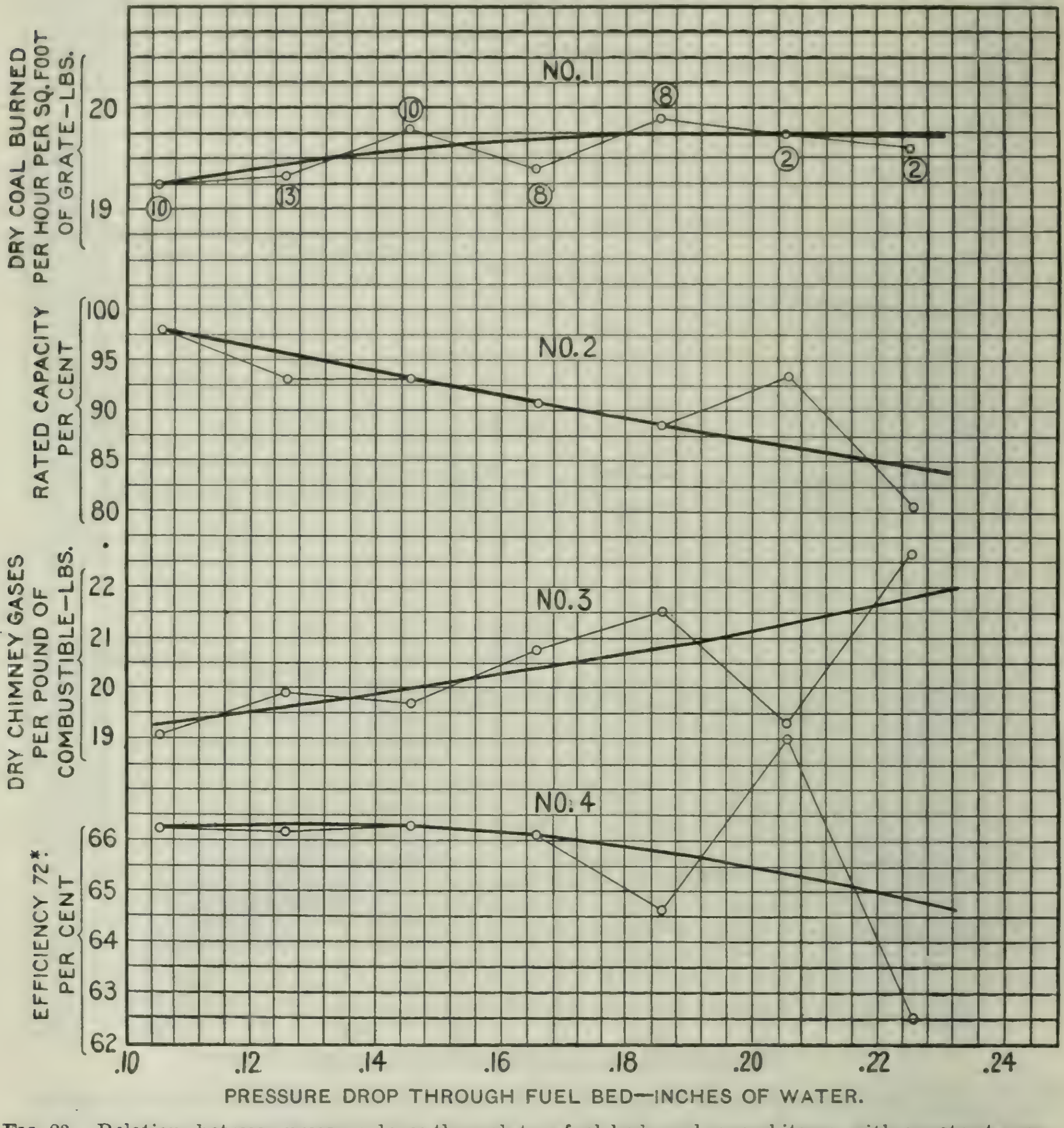

FIG. 23.—Relations between pressure drops through two fuel beds and several items, with constant pressure drop through boilers. Curve 1, pounds of dry coal burned per hour per square foot of grate area; curve 2, percentage of rated capacity developed; curve 3, pounds of dry chimney gases per pound of "combustible;" curve 4, over-all efficiency of furnace and boiler (efficiency 72*), per cent. In platting these curves only those tests were used for which the gas pressure drop through the boiler was 0.35 inch of water.

The classification of figure 22 is based on the pressure drop through the fuel bed. According to curves 1 and 3, it would seem that the rate of combustion and the capacity increase with the pressure drop through the fuel bed. However, if these two curves be compared with curve 2, it becomes evident that the rise in the rate of combustion and the capacity is due to the increasing difference between pressures in the uptake and over the fuel bed. The points of curves 1, 2, and 3 rise and fall together. Curve 4 shows that in general the weight of air used per pound of "combustible" increases with the

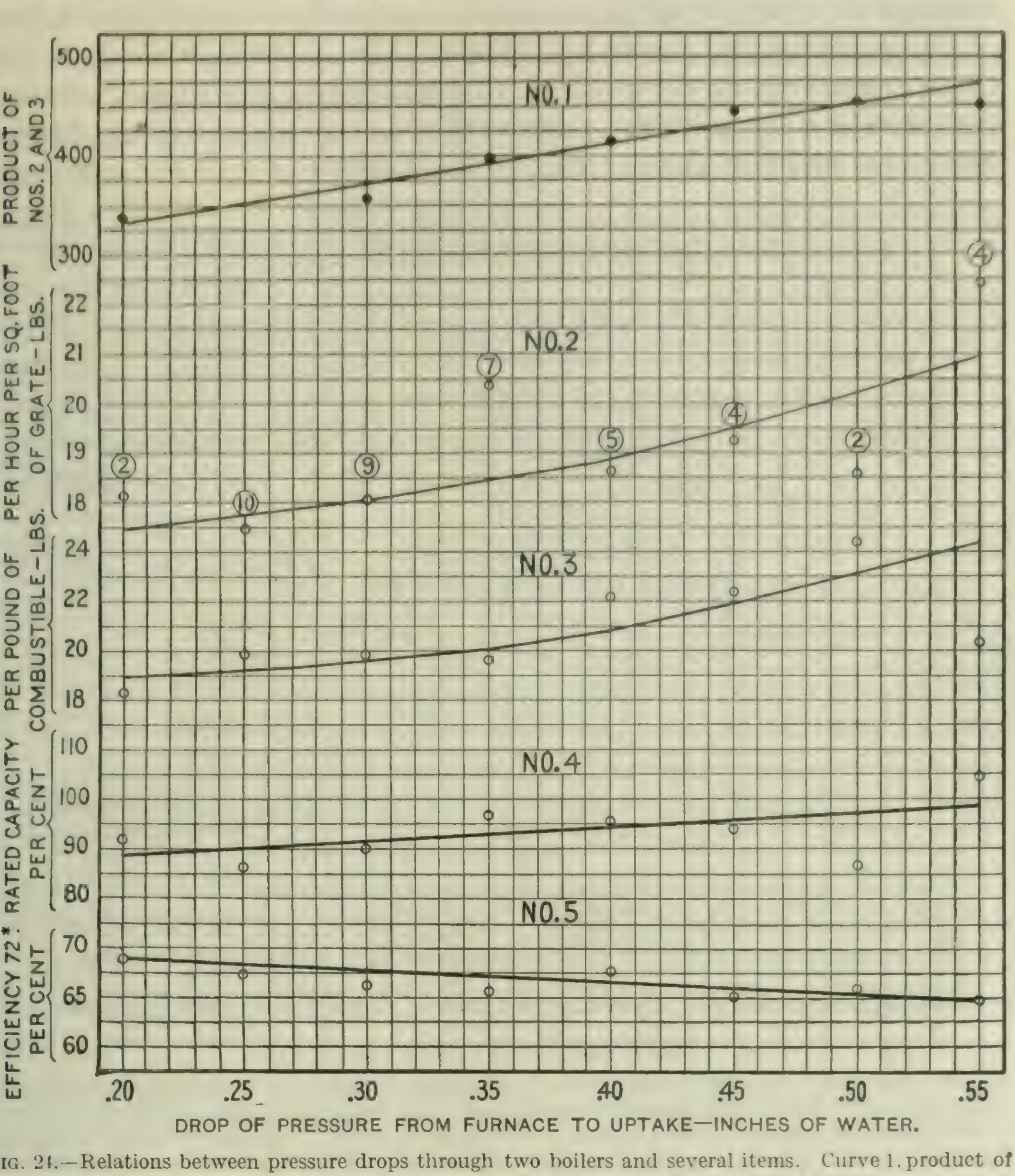

FIG. 24.—Relations between pressure drops through two boilers and several items. Curve 1, product of pounds of dry coal burned per hour per square foot of grate area and pounds of dry chimney gases per pound of "combustible;" curve 2, pounds of dry coal burned per hour per square foot of grate area; curve 3, pounds of dry chimney gases per pound of "combustible;" curve 4, percentage rated capacity of boiler developed; curve 5, over-all efficiency (72*), per cent. In platting these curves only those tests were used for which the gas pressure drop through the fuel bed equaled 0.12 and 0.13 inch of water

pressure drop through the fuel bed, which increase indicates that no economy is gained by raising the resistance of the fuel bed. Curve 5 shows a decided drop in efficiency when the pressure drop through the fuel bed increases. There are probably several causes for this decrease in efficiency, the principal ones being the rise in the rate of combustion and the capacity and the higher percentages of ash in the coals of the tests on the right. It has already been explained in connection with figure 21 why the efficiency decreases when the rate of combustion and capacity increase.

Figure 23 was worked up to show the effect of drop of pressure through the fuel bed alone on the evaporation, without the influence of the pressure drop through the boiler. In compiling this chart only those tests were used for which this latter pressure drop was about 0.35 inch of water. Curve 1 shows that as the pressure in the furnace decreases (that is, as the "draft" increases) the rate of combustion remains nearly constant. Curve 2 shows a decided drop in capacity, which drop, and also the drop in efficiency, can be explained by the indication of curve 3, which shows that as the pressure drop through the fuel bed increases more air is required to burn 1 pound of "combustible," whence results a lower temperature of the gases and a greater loss of heat up the stack and a lower efficiency. The low temperature of the gases reduces their volume so much that, even if their weight passing through per second increases, their velocity remains the same, or may even decrease, which explains the apparent contradiction with statements made in previous paragraphs.

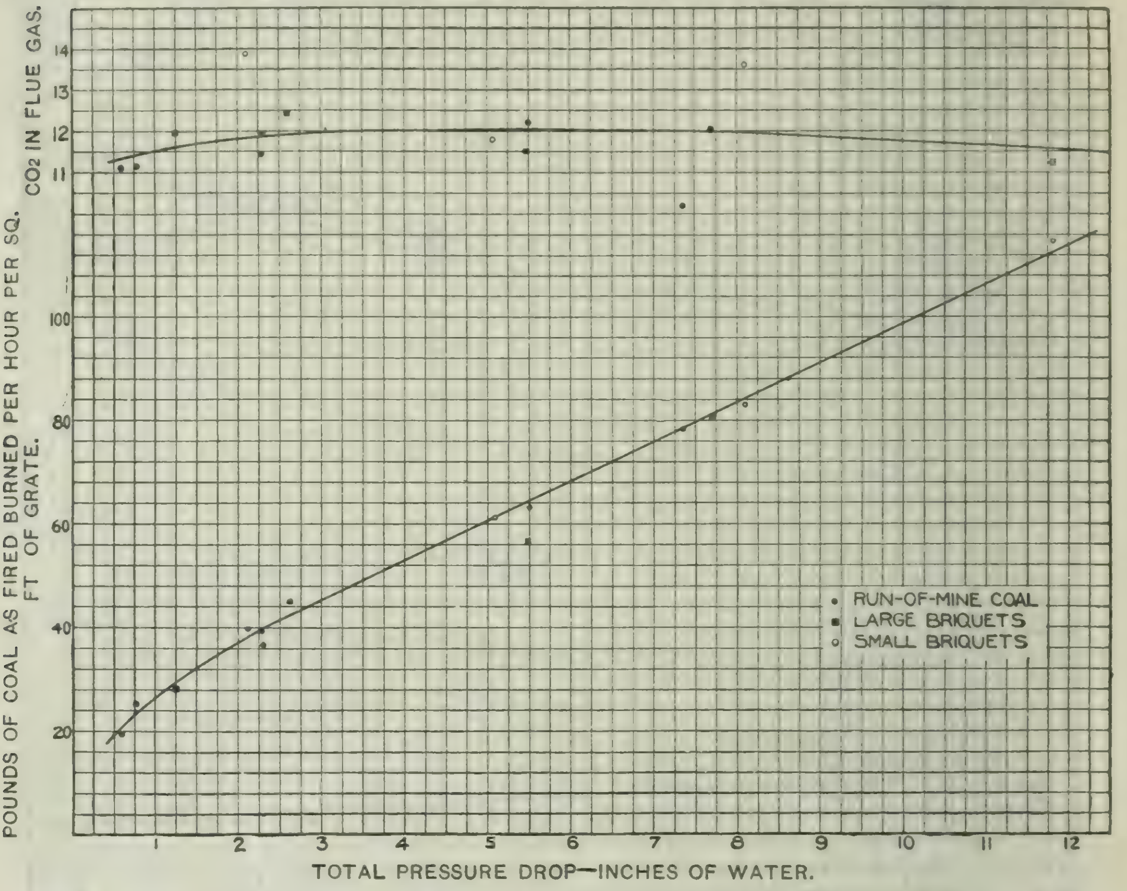

FIG. 25.—Relation, in locomotive tests, between total pressure drop and rate of combustion (lower curve) and percentage of CO_2 in the flue gases (upper curve). The upper curve indicates that the number of pounds of air per pound of coal did not increase with the pressure drop. The points are for individual tests.

Figure 24 is similar to figure 21. In platting this chart only those tests were used for which the average pressure drop through the fuel bed was 0.12 and 0.13 inch of water, so that the pressure in the furnace may be considered a constant amount below the atmosphere. In general this chart agrees with figure 21.

The conclusion which can be drawn from the four charts based on classification of tests according to gas pressures in the boiler setting is that in any one apparatus the rate of combustion and the capacity increase with the difference of pressures in the uptake and the furnace, and not with the pressure drop through the fuel bed alone. Or, stated otherwise, an unduly high pressure drop through the fuel bed is an indication of bad conditions therein, in that the flow of air through it is difficult.

From the charts just discussed the inference must not be drawn that large pressure drops ("drafts") are apt to be accompanied by low efficiencies; in the above cases the coincidences are a consequence of the equipments used, and in some cases of certain properties of the coals burned.

LOCOMOTIVE TESTS BY THE GEOLOGICAL SURVEY AND THE SEABOARD AIR LINE RAILWAY AT PORTSMOUTH, VA.

In order to demonstrate further some of the principles developed or advocated in the preceding pages, such data and results as bear directly on the subject of this bulletin were extracted from 14 locomotive tests and compiled into Table 9. These tests were made with run-of-mine coal, with large square briquets, 6¾ by 4⅜ by 3 inches, and with small oval briquets, 3¼ inches in diameter by 2 inches thick. Both styles of briquets were made expressly for these tests by the Geological Survey at its Norfolk testing plant, from part of the run-of-mine coal.[a] The object of the tests was to determine whether the use of briquets in a steam locomotive would increase the economy and capacity sufficiently to pay for the briquetting of the coal, and whether one kind of briquet possessed any advantages over the other. All tests were made with the locomotive standing in the yards, and the steam was discharged into the steam main of a stationary boiler plant.

The locomotive was a new one of the 10-wheel freight type. The fire box was 104 inches long and 41 inches wide. The height of the crown sheet above the grate was about 55 inches. The fire box contained a brick arch inclosing and supported by five 2½-inch water tubes. A rocking grate of the finger type supported the fuel. The boiler contained 328 tubes, each 2 inches in internal diameter and 14 feet

---

[a] For analysis of coal used, see Bulletin No. 362 of the United States Geological Survey, Mine sampling and chemical analyses of coals tested at Norfolk, Va., in 1907, by J. S. Burrows. A detailed account of the tests will be found in Bulletin No. 412, by W. T. Ray and H. Kreisinger.

1⅞ inches long. The pressure drop, or draft, was produced as usual by the small steam jet or by discharging steam directly from the boiler through the exhaust nozzle; when using the latter method the cylinder valves were removed and the discharge of the steam producing the pressure drop was regulated by the main throttle.

The most significant feature of the results of these tests as applied to the subject of this bulletin is that the rate of combustion keeps up with the total pressure drop, as might be predicted from the relation between the total pressure drop and the rate of flow of air, obtained from experiments on the flow of air through beds of shot. This feature is brought out very prominently by the lower curve of figure 25. It shows that for a certain range the rate of combustion increases with the total drop, and that the increase in the rate of combustion is faster than the law of its proportionality to the square root of the total drop would suggest. Thus, at a total drop of 3 inches of water the rate of combustion is 45 pounds of coal per square foot of grate surface per hour; at a total pressure drop of 9 inches of water it is 90 pounds, which is twice as much as in the first instance, whereas if the square-root rule held the rate of combustion would be only the square root of $9 \div 3 = 1.73$ times as large, or only about 76 pounds.

The points of the upper curve are somewhat irregular, but in general they show that the air supply per pound of coal remains about constant, or, rather, that the rate of combustion keeps up with the air supply.

Strictly speaking, the lower curve of figure 25 shows the rate of disappearance of coal from the grate and not the rate of combustion, because part of the coal was not gasified but went up the stack in the form of sparks. However, the amount of sparks seldom exceeded 5 per cent of the coal fired, so that the curve would not be changed very much if correction were made for the coal lost in sparks.

It may be interesting to compare the indication of figure 25 with that of figure 11 and with the discussion of the latter beginning on page 31. It is stated there that if a given boiler uses up 2 per cent of the total steam generated in operating the fan when the boiler is working at 100 per cent of its rated capacity, the consumption of steam by the fan will rise to 6.5 per cent of the steam generated if the capacity of the boiler be doubled, and to 12 per cent if the capacity be trebled. Turning now to figure 25, let us assume that the capacity of the boiler increases directly with the nominal rate of combustion. Starting with the point at the total pressure drop of 2 inches, where the rate of combustion is 37 pounds, the following will be the pressure drops and relative amounts of work required of the fan for doubled and trebled rates of combustion and capacities. The amount of work done by the fan in each case is figured from the relative volume of air and the pressure it is moved against by the formula "Work of fan is proportional to volume × pressure." Pressure drops are taken from the curve of figure 25.

TABLE 9.—*Data and results of locomotive tests made at the Seaboard Air Line Railway shops at Portsmouth, Va.*

No. of test.	Kind of fuel.	Pressures (drafts), Inches of water.				Weight of coal as fired burned per hour per square foot of grate.	Equivalent evaporation per pound of dry coal.	Horsepower developed.	Per cent of CO_2 in flue gas.	Per cent of O_2 in flue gas.	Per cent of CO in flue gas.	Per cent of N_2 in flue gas.	Average thickness of fire.
		Near nozzle.	At the end of tubes.	Over arch.	Over fuel bed.								
						Lbs.	*Lbs.*						*In.*
1	Run of mine....	0.77	0.61	0.48	0.39	25.5	11.91	251.8	11.45	6.92		81.63	8
2	....do..	2.30	1.86	1.10	1.05	36.5	11.44	343.0	11.96	7.00	0.23	80.81	11
3	....do...	2.27	1.86	1.12	.87	39.4	10.81	349.0	11.46	7.49	.1	80.95	12
4	....do..........	.59	.53	.41	.33	19.2	11.52	183.0	11.10	7.84	.23	80.83	6
5	Large briquets..	1.25	1.00	.70	.57	27.9	11.24	260.0	11.96	7.07	.14	80.83	15
6	....do..........	2.63	1.96	1.37	1.03	45.0	11.10	410.0	12.45	5.87	.22	81.46	15
7	.....do.........	5.48	3.69	2.54	1.95	56.3	10.93	504.0	11.50	7.08	.17	81.25	18
8	.....do..........	7.70	4.10	3.01	......	80.2	10.18	672.0	12.05	6.93	.15	80.87	16
9	Run of mine [a]..	7.36	4.54	2.65	......	78.1	8.66	542.0	10.16	8.49	.13	81.22	16
10	Small briquets..	2.11	1.59	.56	......	39.8	11.21	374.0	13.87	4.75	.25	81.13	7
11	.....do..........	8.10	5.48	2.73	......	82.4	10.53	723.0	13.57	4.49	.20	81.91	12
12	.....do.........	5.07	3.69	1.95	......	61.1	10.68	548.0	11.78	6.74	.30	81.18	8
13	Run of mine....	5.50	3.89	2.41	......	63.0	9.86	501.0	12.20	6.94	.05	80.81	15
14	Small briquets [b]	11.8	8.74	3.10	......	114.6	8.88	827.0	11.15	7.52	.20	81.13	16

[a] Coal wet and mostly slack.

[b] About 30 per cent of briquet had crumbled.

Pressure drops and relative amounts of work required of fan for doubled and trebled rates of combustion and capacities.

Rated capacity.	Rate of combustion.	Pressure drop, taken from curves.	Total steam consumed by fans.	Relative total work required from fan.
Per cent.			*Per cent.*	
100	37	2.00	[a] 2.00	1.00
200	74	6.85	[b] 6.85	6.85
300	111	11.65	[b] 11.65	17.50

[a] Assumed.

[b] Calculated.

In the above comparison the rate of combustion was taken, rather than the horsepower developed by the locomotive boiler, because the consideration of the former is more nearly parallel to the experiments on the flow of air through beds of shot.

Figure 26 shows how the boiler horsepower developed by the locomotive increases with the total pressure drop from ash pit to stack. The points for the three styles of fuel do not fall so nicely in one line as they do in figure 25. Evidently the combustion was not as good with run-of-mine coal as it was with briquets, and for that reason the capacity does not increase as fast with rising total pressure drop. The location of the points is such as to make it advisable to pass three curves through them, one for each style of fuel. The highest point of the small briquet curve is apparently too low; before making these tests the briquets had been transferred several times from one tender to another, so that about 35 per cent of them had crumbled before the test. This condition undoubtedly pulls the point down toward the run-of-mine curve. The slower increase in boiler horsepower of the curve for run-of-mine coal is largely due to the fact that the coal contained a high percentage of slack which was carried by the strong current of gases through the furnace and boiler and out through the stack. In the calculations this loss is charged against the heat-absorbing ability of the boiler, even though it does not increase the rate of steam production in any way, and even though it absorbs fan work in being moved along.

According to the curves of figure 26 the increase in total pressure drop required to develop twice a given horsepower would be as follows:

Increase in total pressure drop required to develop twice a given horsepower.

SMALL BRIQUETS.

	Total pressure drop in inches of water.	Boiler horsepower developed.
Case 1	2.0	365
Case 2	8.5	730

Ratio of pressure drops of cases 2 and 1=8.5÷2=4.25.

LARGE BRIQUETS.

Case 1	2.0	332
Case 2	7.7	664

Ratio of pressure drops of cases 2 and 1=7.7÷2.0=3.85.

In order, then, to double the capacity the total pressure drop must be multiplied by 4.25 when burning these particular small briquets, and by 3.85 when burning these particular large briquets, in this particular furnace. With the run-of-mine coal it would be necessary to multiply the total pressure drop by about 10.2 to obtain the same increase. It is evident that run-of-mine coal containing a high percentage of slack is not fit to use for high capacities with high pressure drops through the fuel bed, for reasons already stated, one of them being the carrying up of fine coal unburned. Fuels having pieces of uniform size, such as briquets, are better suited for use in this manner.

The average of the ratios of the pressure drops in the two above cases for the two styles of briquets is about 4, or 2^2. Taking into consideration also the fact that at such higher pressures at least twice the weight of gas must be put through the fuel bed and boiler, the ratio of the work required from the fan in the above two cases will be as given in the last column of the table below:

	Relative capacity.	Relative pressure drop.	Relative weight of gas (volume).	Relative work required of fan.	Relative work required of fan, considering case 1 as unity.
Case 1	100	2	1	2	1 or 1^3
Case 2	200	2×2^2	2	16	8 or 2^3

Therefore, to double the capacity of an existing boiler (without reballling or otherwise changing it) the work of the fan must be multiplied by 8—that is, by 2^3. On studying figure 26 it would seem that with a well-designed furnace and with a fuel of uniform size the same relation as above would hold for a case of trebled capacity, as given below:

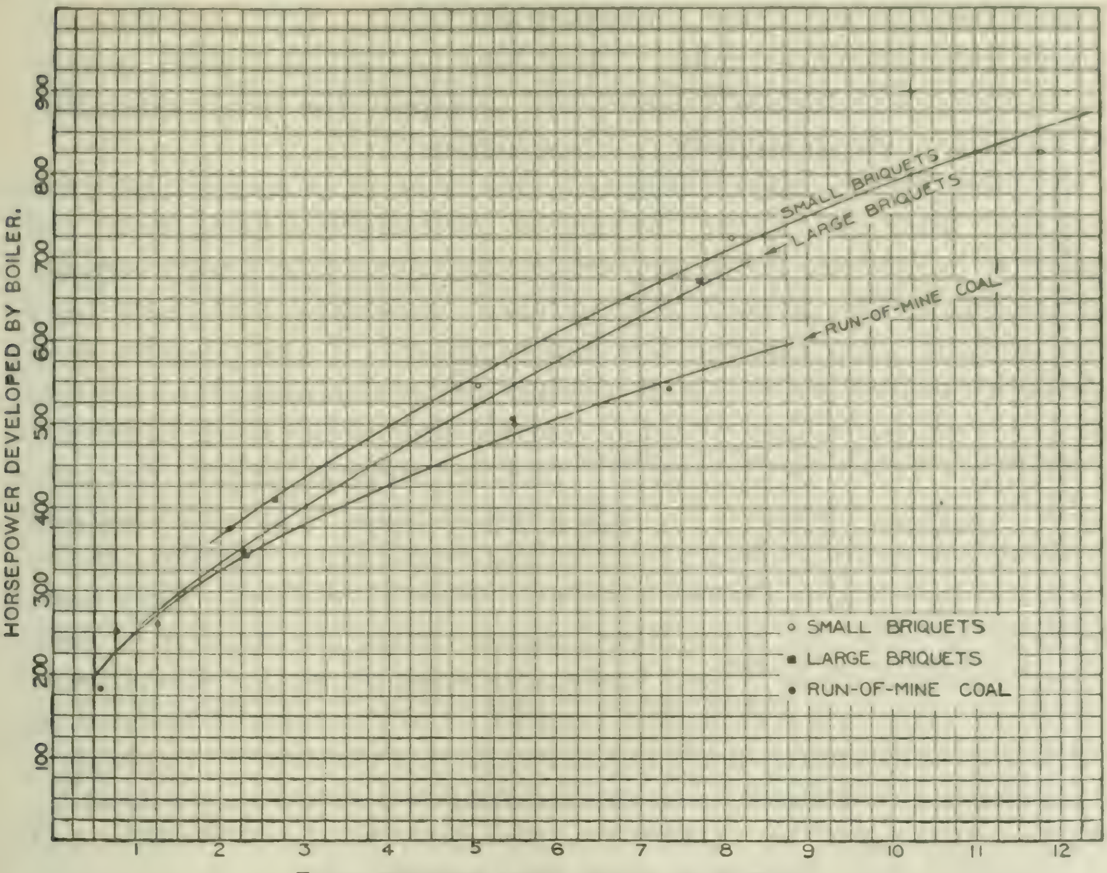

FIG. 26.—Relation, in locomotive tests, between the total pressure drop and the boiler horsepower developed. The points are individual tests on run-of-mine coal, large square briquets and small oval briquets.

	Relative capacity.	Relative pressure drop.	Relative weight of gas (volume).	Relative work required of fan.	Relative work required of fan, considering case 1 as unity.
Case 3	300	2×3^2	3	54	27 or 3^3

The relative work in the three above cases is obtained by multiplying together the relative weights of the gases (volumes) and the relative pressures against which the volumes are displaced, which procedure is in accordance with the well-known formula, "Work is proportional to volume × pressure."

The figures in the preceding three cases state that the work required of the fan varies as the cube of the capacity developed by the boiler. This relation is found to be approximately correct, at least for the tests of figures 25 and 26. With boiler outfits designed for high capacity the work of the fan might be far less than indicated above, while with some of the existing outfits it would be more.

A caution is in place here. The attempt must not be made to put more air through existing boilers by running the fans a great deal faster, because the power consumed will increase far faster than the above calculations estimate. New fans and engines must usually be installed of sufficiently larger size to supply the larger quantities of air at as high an efficiency, if not higher.

As has already been suggested, one way of reducing the work required from the fan in the case of doubling the capacity of the boiler is to increase the grate surface, so as to avoid a high increase of pressure drop through the fuel bed, increasing materially only the pressure drop through the boiler proper. A low pressure drop through the fuel bed would also insure better combustion of the fine particles of coal which would be carried out of the stack unburned if high gas velocities through the fuel bed were employed, the high velocities being obtained by high pressure drops. This last method is being successfully used by H. G. Stott and W. S. Findley, of the Interborough Rapid Transit Company, New York City. They have recently installed an extra Roney stoker under the rear end of each of several Babcock & Wilcox boilers, with the result that the amount of steam produced was nearly doubled, the combined efficiency of the boiler and furnace dropping only about 3 per cent. A complete description of the outfits and the results is given in a paper read by Walter S. Findley, jr., before the American Institute of Electrical Engineers in December, 1907. In this case the pressure drop through the fuel bed was the same as with the single stoker, or perhaps decreased slightly. Of course, the pressure drop through the boiler proper increased considerably. An electrical engineer would say that the above experimenters put two fuel beds in parallel and with the same potential drop obtained twice the current (weight of gases). The same result could have been obtained by thickening somewhat the fuel bed on the single stoker and increasing the pressure drop through it, in which case the electrical engineer would say that the experimenters put two fuel beds in series and by increasing the drop of potential obtained twice the current (twice the weight of gases).

The method of increasing the grate area is a promising one because it requires less work from the fans; it is especially to be preferred in those cases where there is a high percentage of slack in the coal, as already explained.

The figures and principles derived from the experiments and tests presented in this bulletin may not be applicable directly to special problems; they suggest methods by which each problem can be studied and its successful solution brought about. Further experiments with laboratory apparatus as well as with hot fuel beds are desirable before more accurate figures can be given. The Geological Survey contemplates the making of such experiments in the near future, the results to be worked up and published in the next bulletin on "Drafts."

SUMMARY.

The substance of this bulletin may be summarized as follows:

If the resistance to the flow of gas remains unchanged, the pressure drop through any portion of the gas passage bears a constant ratio to the total pressure drop.

If the total pressure drop from ash pit to uptake remains constant, the pressure drop through any portion of the gas passage varies with the resistance to the flow of gas through that particular portion. Thus with a constant total drop from the ash pit to the uptake the pressure drop through the grate and fuel bed varies with the resistance of the grate and fuel bed, the variation being in the same direction but not of proportional magnitude.

If the resistance of any portion of the gas passage remains constant, the weight of gas passing through that portion varies as some power of the pressure drop through it. The index of the power is approximately $\frac{1}{2}$, so that in order to double the weight of gas passing through, the pressure drop must be quadrupled, and in order to treble it the pressure drop must be made nine times as great.

The above three statements are general for all conditions and for all combinations of "forced" and "induced" "draft."

There is really no difference between "forced" and "induced" "draft," provided the setting is tight. The volumetric percentage of "dead" corners in a boiler is the same in either case.

"With gases there is no pulling, only pushing." Gases travel from places of higher pressure to those of lower, the motion of the gas occurring because of its expansion.

The term "draft" is indefinite, being applied sometimes to the motion of gases and sometimes to the cause of the motion—that is, to the pressure difference.

Experiments shedding light on the flow of gases through boilers were made in a laboratory by passing air through two beds of lead shot. The results of the experiments are expressed in the following brief paragraphs:

The rate of flow of air through a bed of shot of constant thickness is approximately proportional to the square root of the pressure drop through the bed.

As the thickness of the beds of shot increase, the weight of air passing through per minute decreases very rapidly at first, then more and more slowly.

To put air at the same rate through twice as thick a bed of shot requires twice the pressure difference between the two sides of the bed and twice the work must be expended.

If the height (number of rows of tubes) of a cross-flow type of water-tube boiler be doubled, or if the length of the tubes of a parallel-flow type of water-tube boiler be doubled, or if the thickness of a fuel bed be doubled, it is likely that the work required of a fan will be about doubled if the same weight of gas is to be passed through per minute.

If two or three times the usual amount of gases be forced through a stoker and boiler so as to produce nearly two or three times as much steam, the total work expended on the fans will be increased perhaps 8 and 27 times, respectively (2^3 and 3^3). Suppose that it takes 60 pounds of steam per hour to run the fan when developing 100 boiler horsepower in a certain boiler, to develop 200 horsepower in the same boiler a fan of the same efficiency would use $60 \times 8 = 480$ pounds of steam, and to develop 300 horsepower a third fan of the same efficiency would use $60 \times 27 = 1,620$ pounds. Expressed in percentage, the consumption of steam in the three cases would be as follows, taking as a boiler horsepower 30 pounds of steam produced under 70 pounds gage pressure from feed water at 100° F.:

Fan consumption of steam as a percentage of total steam generation.

	Boiler horsepower.	Total steam generated per hour.	Total steam consumed per hour by fans.	Percentage of steam used by fans.
		Pounds.	*Pounds.*	
Case 1........	100	30×100=3,000	60	60:3,000= 2
Case 2........	200	30×200=6,000	480	480:6,000= 8
Case 3........	300	30×300=9,000	1,620	1,620:9,000=18

This greater proportionate expenditure of steam would probably be saved in other operating costs, besides which there would be the great advantage of working the investment two or three times as hard.

There is, however, a limit beyond which it would not pay to increase the total pressure drop in order to raise the capacity of a boiler. Assume that the work applied to the fan would continue to increase as in the above three cases, starting the same at 2 per cent. With higher capacities the steam consumption of the fans would be as given below:

Boiler horse-power.	Percentage of steam used by fan.	Boiler horse-power.	Percentage of steam used by fan.
100	2	500	50
200	8	600	72
300	18	700	98
400	32	800	128

This table shows that it would be impossible to multiply the capacity by more than 7. Beyond this the fan would take more steam than the boiler would make. At 5 times the original capacity the fan would take about half the steam. Doubling, trebling, and perhaps with larger grate areas even quadrupling the rate of working a boiler seems to be sound commercial practice. Furthermore, by carefully designing a fan the above steam consumption could nearly be cut in half. This we must admit if we study efficiency tests made on fans of various makes by trustworthy experimenters, who have shown that the efficiency of a blower from the shaft to air delivered lies ordinarily between 10 and 50 per cent.

Increasing the length of a multitubular boiler and leaving the internal diameter of the tubes the same seems in some cases to increase slightly the total amount of heat absorbed when the boiler is working under the same pressure (draft) difference between the two ends of the tubes, although the weight of air passing through is less.

A large pressure drop through the fuel bed (or a high draft above the fire) does not necessarily mean that the rate of combustion is high; it is likely to mean the opposite. High pressure drop through the fuel bed always means high resistance in it to the flow of gas.

The pressure drop through the fuel bed, or the draft over the fire, is significant only when considered in connection with the total pressure drop.

The capacity of a boiler increases with the difference between the pressures in the uptake and over the fire.

With constant total pressure drop (total draft) the capacity of a boiler decreases as the pressure drop through the fuel bed increases.

GLOSSARY.

ASH PIT.—Used in this bulletin to mean the space under the grate through which air must pass before entering the grate and fuel bed.

COMBUSTIBLE.—A loose name and misnomer for the substance properly described as "coal free from moisture, sulphur, and ash." In this bulletin it means "coal free from moisture and ash."

DRAFT.—This term is sometimes applied to the motion of gases and sometimes to the difference of pressures producing the motion. To speak of draft being absorbed by sharp turns can not mean anything else than that the velocity of the gases is reduced. To speak of a draft of 1 inch of water can not mean anything else than that the difference between the pressures at two points is sufficient to support a column of water 1 inch high. The vague term draft probably originated from the mistaken idea that something was pulling or drawing the gas. See pages 6–9 for arguments that there is really no such motive power effective in the movement of gases.

EXHAUST FAN.—Commonly called induced-draft fan.

FUEL BED.—The mass of burning fuel on a grate.

HOOD.—See Uptake.

PRESSURE DROP.—The pressure drop through any portion of a gas passage is the difference between the pressures at the two ends of the portion. It is equal to the difference between "drafts" at the two points.

Total pressure drop is the difference between the pressures at the two extreme ends of a gas passage, including all the component portions.

PRESSURE FAN.—Commonly called forced-draft fan.

UPTAKE, sometimes called HOOD.—The conical passage connecting the place where the gases leave the boiler proper with the flue leading to the chimney. The pressures taken in the uptake were obtained within 2 or 3 feet of the last tubes of the boiler proper.

PUBLICATIONS ON FUEL TESTING.

The following publications, except those to which a price is affixed, can be obtained free of cost by applying to the Director of the Bureau of Mines, Washington, D. C. The priced publications can be purchased from the Superintendent of Documents, Government Printing Office, Washington, D. C.

PUBLICATIONS OF THE BUREAU OF MINES.

BULLETIN 1. The volatile matter of coal, by H. C. Porter and F. K. Ovitz, 1910. 56 pp., 1 pl.

BULLETIN 2. North Dakota lignite as a fuel for power-plant boilers, by D. T. Randall and Henry Kreisinger. 1910. 42 pp., 1 pl.

BULLETIN 3. The coke industry of the United States as related to the foundry, by Richard Moldenke. 1910. 32 pp.

BULLETIN 4. Features of producer-gas power-plant development in Europe, by R. H. Fernald. 1910. 27 pp., 4 pls.

BULLETIN 5. Washing and coking tests of coal at the fuel-testing plant, Denver, Colo., July 1, 1908, to June 30, 1909, by A. W. Belden, G. R. Delamater, J. W. Groves, and K. M. Way. 1910. 62 pp.

BULLETIN 7. Essential factor in the formation of producer gas, by J. K. Clement, L. H. Adams, and C. N. Haskins. 1911. 58 pp., 1 pl.

BULLETIN 8. The flow of heat through furnace walls, by W. T. Ray and Henry Kreisinger. 1911. 32 pp.

BULLETIN 9. Recent development of the producer-gas power plant in the United States, by R. H. Fernald. 1909. 82 pp., 2 pls. Reprint of United States Geological Survey Bulletin 416.

BULLETIN 11. The purchase of coal by the Government under specifications, by G. S. Pope. 1911. 80 pp. Reprint of United States Geological Survey Bulletin 428.

BULLETIN 12. Apparatus and methods for the sampling and analysis of furnace gases, by J. C. W. Frazer and E. J. Hoffman. 1911. 22 pp.

BULLETIN 13. Résumé of producer-gas investigations, October 1, 1904, to June 30, 1910, by R. H. Fernald and C. D. Smith. 1911. 378 pp., 12 pls.

BULLETIN 14. Briqueting tests of lignite at Pittsburgh, Pa., 1908–9, by C. L. Wright. 1911. 58 pp., 11 pls.

PUBLICATIONS OF THE UNITED STATES GEOLOGICAL SURVEY.

BULLETIN 261. Preliminary report on the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, in St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1905. 172 pp. 10 cents.

PROFESSIONAL PAPER 48. Report on the operations of the coal-testing plant of the United States Geological Survey at the Louisiana Purchase Exposition, St. Louis, Mo., 1904; E. W. Parker, J. A. Holmes, M. R. Campbell, committee in charge. 1906. In three parts. 1492 pp., 13 pls. $1.50.

BULLETIN 290. Preliminary report on the operations of the fuel-testing plant of the United States Geological Survey at St. Louis, Mo., 1905, by J. A. Holmes. 1906. 240 pp. 20 cents.

BULLETIN 325. A study of four hundred steaming tests made at the fuel-testing plant, St. Louis, Mo., 1904, 1905, and 1906, by L. P. Breckenridge. 1907. 196 pp. 20 cents.

BULLETIN 332. Report of the United States fuel-testing plant at St. Louis, Mo., January 1, 1906, to June 30, 1907; J. A. Holmes, in charge. 1908. 299 pp. 25 cents.

BULLETIN 336. Washing and coking tests of coal and cupola tests of coke, by Richard Moldenke, A. W. Belden, and G. R. Delamater. 1908. 76 pp. 10 cents.

BULLETIN 362. Mine sampling and chemical analyses of coals tested at the United States fuel-testing plant, Norfolk, Va., in 1907, by J. S. Burrows. 1908. 23 pp. 5 cents.

BULLETIN 363. Comparative tests of run-of-mine and briqueted coal on locomotives, including torpedo-boat tests and some foreign specifications for briqueted fuel, by W. F. M. Goss. 1908. 57 pp., 4 pls.

BULLETIN 368. Washing and coking tests of coal at Denver, Colo., by A. W. Belden, G. R. Delamater, and J. W. Groves. 1909. 54 pp., 2 pls.

BULLETIN 385. Briqueting tests at the United States fuel-testing plant, Norfolk, Va., 1907–8, by C. L. Wright. 1909. 41 pp., 9 pls.

BULLETIN 392. Comparative deductions from gasoline and alcohol tests on internal combustion engines, by R. M. Strong. 1909. 38 pp.

BULLETIN 393. Incidental problems in gas-producer tests, by R. H. Fernald, C. D. Smith, J. K. Clement, and H. A. Grine. 1909. 29 pp.

BULLETIN 402. The utilization of fuel in locomotive practice, by W. F. M. Goss. 1909. 28 pp.

BULLETIN 403. Comparative tests of run-of-mine and briqueted coal on the torpedo boat *Biddle*, by Walter T. Ray and Henry Kreisinger. 1909. 49 pp.

BULLETIN 412. Tests of run-of-mine and briqueted coal in a locomotive boiler, by Walter T. Ray and Henry Kreisinger. 1909. 32 pp.

○

University of Toronto
Library

DO NOT
REMOVE
THE
CARD
FROM
THIS
POCKET

Acme Library Card Pocket
Under Pat. "Ref. Index File"
Made by LIBRARY BUREAU